The Report Committee for Cody Aaron Hill
Certifies that this is the approved version of the following report:

Grid-Scale Battery Energy Storage Systems

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________________

Alexis Kwasinski

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Dongmei Chen

Grid-Scale Battery Energy Storage Systems

by

Cody Aaron Hill, B.S. ECE

Report

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Abstract

Grid-Scale Battery Energy Storage Systems

Cody Aaron Hill, MSE

The University of Texas at Austin, 2013

Supervisor: Alexis Kwasinski

This report presents an overview of the engineering considerations involved in the design of grid-scale battery energy storage systems. Grid-scale is defined here as systems over 1 MW in rated power, typically operated by a utility, independent power producer, or Independent System Operator (ISO). The physical components of a BESS are presented and explained, including power electronics, an introduction to various commercially available battery technologies, necessary control systems, and balance of plant hardware. Also presented are a variety of real-world applications of battery energy storage systems, showing how the specific application determines what mix of technology will be selected when designing the system, as well as explaining the foundation for the control algorithms.

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I. INTRODUCTION

This report presents an overview of the engineering considerations involved in the design of grid-scale battery energy storage systems. Grid-scale is defined here as systems over 1 MW in rated power, typically operated by either a utility, power producer, or Independent System Operator (ISO). In Section II, the physical components of a BESS are presented and explained, including power electronics, an introduction to various commercially available battery technologies, necessary control systems, and critical balance of plant hardware. Section III presents a variety of real-world applications of battery energy storage systems, and shows how the specific application determines what mix of technology will be selected when designing the system. The report references both academic and professional sources, as well as drawing on the author's experience as a Systems Engineer at Xtreme Power, a private company in Kyle, Texas that has developed 75MW worth of megawatt-scale BESS in the United States and China.

II. BATTERY ENERGY STORAGE SYSTEM COMPONENTS

Overview

A grid-scale BESS consists of a battery bank, control system, power electronics interface for ac-dc power conversion, protective circuitry, balance of plant hardware, and a transformer to convert the BESS output to the transmission or distribution system voltage level. Each of these is discussed in the sub-sections below. A conceptual diagram of a simple BESS is shown in Figure 1.

Commercially available batteries come in a variety of chemistries and form factors, and selecting the right battery for the application is critical to the safety, system

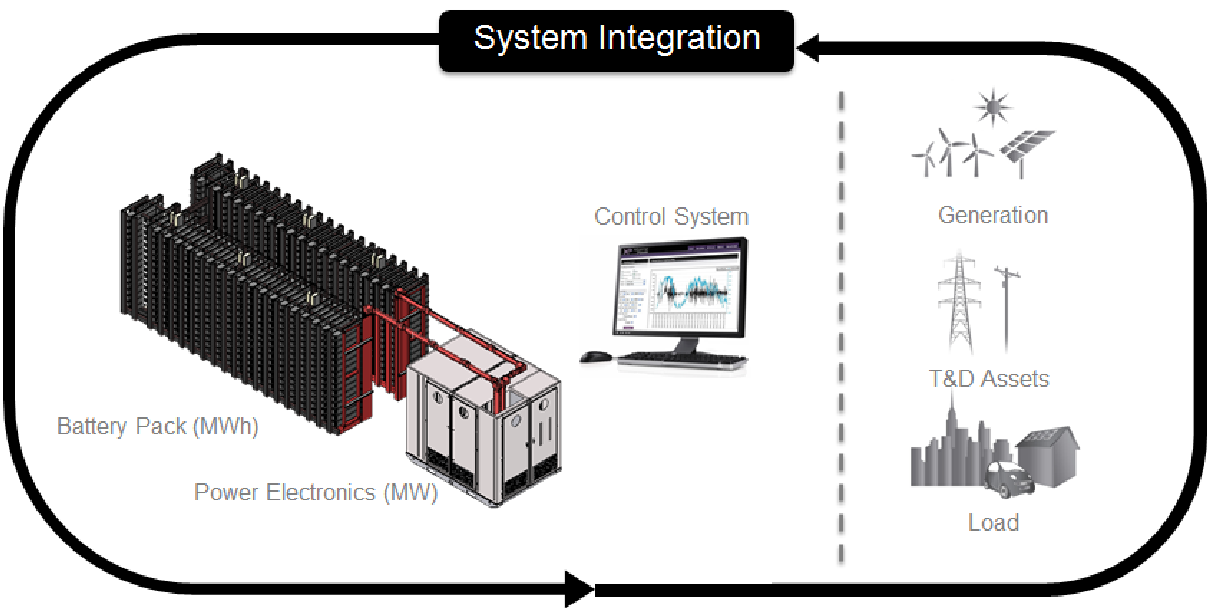

Figure 1: The components of an integrated BESS, and three possible power system assets that a BESS might be integrated to improve the operation of. Source: Xtreme Power

lifetime, and economics of a BESS project [1]. Many battery cells are connected in a combination of series and parallel electrical connections to achieve the desired capacity and operating voltage of the system. In order to charge and discharge the battery from the electric grid, a power conversion system (PCS) is required to convert between AC grid power and DC battery power. The PCS operation must be carefully controlled in order to safely operate the batteries while meeting the requirements of the project application. Lastly, a BESS will have a variety of balance of plant hardware designed to maintain the desired temperature and airflow of system components during operation, as well as having fire detection, fire suppression, and other safety related functions. [2]

There are two main schools of thought regarding deployment of BESS technologies on the electric power distribution system. One is to provide centralized storage at the MW level at the distribution substation. The other camp would prefer to see smaller energy storage systems distributed on the distribution feeders, networked together and remotely controlled at the substation. Advantages to centralized storage include easy access to substation electrical and SCADA equipment, simplified control schemes, economies of scale, and the fact that there is already utility-owned land available behind the substation fence. The argument for small scale, also known as community energy storage (CES) is made in [3] by engineers from American Electric Power. The ideal sizing and location will vary from site to site and according to the application. In either the centralized case or the case of aggregated CES units, the design considerations in this report are applicable.

Batteries

A battery is made up of two or more electrochemical cells that store energy. Each cell consists of a cathode, anode, electrolyte, and its housing. There are many types of commercially available batteries, and they are classified as either primary (one-use) or secondary (rechargeable) [4]. Grid-scale batteries are built from a large number of rechargeable cells, and the industry is currently dominated by Lead-Acid, Lithium Ion, and Molten Sodium chemistries. Other technologies show considerable promise for grid applications, but have yet to be deployed in many systems with power ratings above 1MW. Such technologies include flow batteries such as Vanadium Redox and Zinc Bromine [5], as well as Sodium Ion [6], and Liquid Metal batteries [7], which are still effectively in the lab and awaiting ramp-up to commercial scale production.

There are many considerations to take into account when selecting a battery for an application. The most important are Safety, Cost, Life Span, Energy, Power, and Performance across a range of ambient conditions such as temperature and humidity. The duty cycle of the application is also an important consideration, as some technologies degrade rapidly when kept at low or partial states of charge. Optimizing the design of a battery for any one parameter listed above will typically result in tradeoffs that reduce a battery's performance on one or more of the other parameters. As such, there is no one perfect chemistry for all applications [2], and the cliché that one should "pick the right tool for the job" holds true.

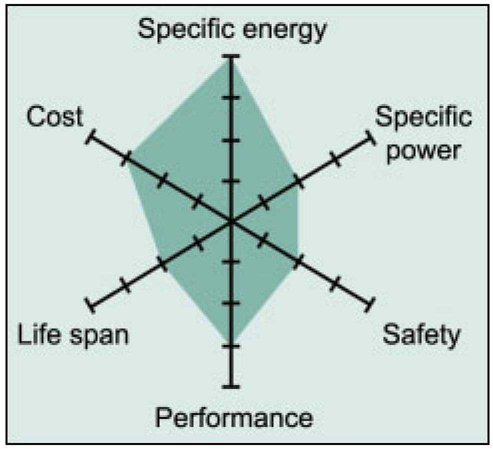

Figure 2: Spider Web plot illustrating battery strengths and weaknesses for the LiCoO2 battery common in consumer electronic devices.

Batteries' strengths and weaknesses can be compared at a glance through the use of hexagonal Spider Web plots, such as the one shown in Figure 2 for a Lithium Cobalt Oxide battery, commonly found in cell phones [8]. The further from the center a battery lands in any of the 6 criterion axes, the better that battery ranks in this regard. The following key explains each of the key parameters shown:

1. Specific Energy – energy capacity of the battery, can be either per-unit mass or volume.
2. Specific Power – the ability to deliver high current. This is sometimes referred to as Max C Rate, which indicates the highest operating current a battery is designed to sustain. Some batteries have one maximum rate for continuous operation, and another for "pulse" power, defined as a high rate discharge for some number of seconds. This is important for some applications.

3. Safety – when a battery fails, how dangerous is it? Some batteries turn into useless bricks when they fail, while others can fail in the form of a powerful explosion that may harm personnel and equipment nearby. Due to the high numbers of cells in a grid-scale battery, the safety of each cell is of critical importance, and various high-profile battery fires have harmed the industry in recent years [9,10].
4. Performance – the ability of a battery to operate across a range of hot and cold ambient temperatures, various humidity levels, etc.
5. Life Span – how long a battery will last. This is typically in reference to cycle life, which means how many times a battery can be repeatedly charged and discharged. Also important is calendar life and shelf life, which indicate how many years a battery can be expected to operate or sit in storage without serious degradation. Many utility projects are expected to have lifetimes of 10 or more years, and the cost of battery replacement factors into the lifetime cost of ownership of the BESS.
6. Cost – the capital cost of purchasing the battery. This is largely a function of manufacturing scale, the cost and availability of materials, as well as the difficulty of the manufacturing processes associated with the technology.

Selecting a BESS's battery technology often starts from an analysis of the expected duty cycle and the duration of the application. Batteries that can deliver higher power compared to their energy capacity (higher C-Rate batteries) tend to be more expensive per kWh of battery installed. This being the case, it is not cost-effective to select a high power battery for a long duration application, and most of that power capacity will not be used. On the other hand, it takes many low C-Rate batteries connected in parallel to deliver high power, and if the long duration is not required, the system is not cost effective. The chart in Figure 3 arranges a variety of battery technologies according to the duration in which they are most cost-effective.

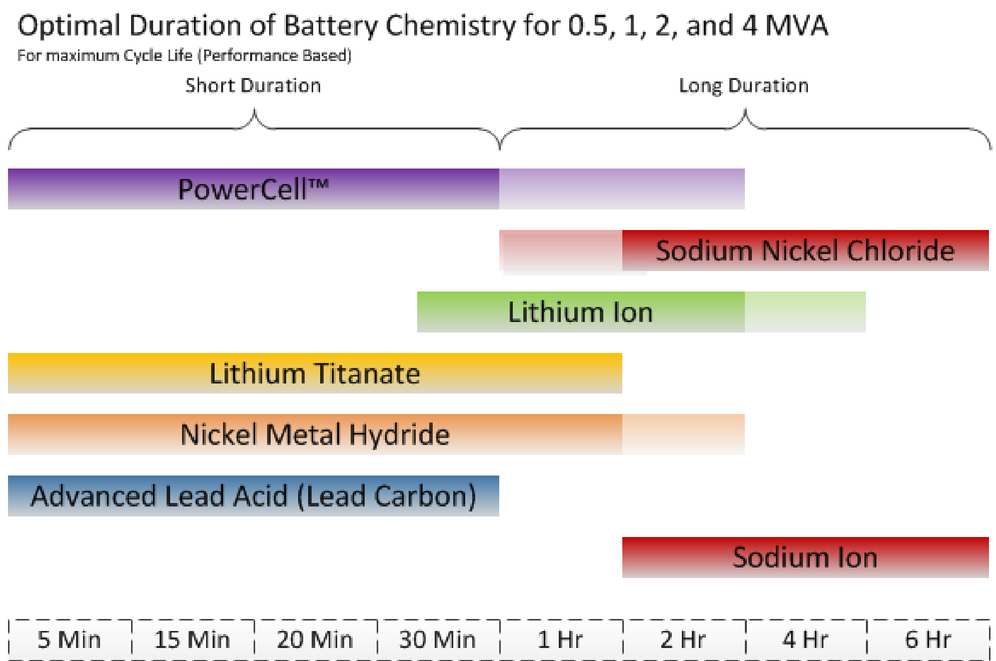

Figure 3: Battery chemistry optimal durations. Source: Xtreme Power, IEEE Presentation 2012. Note: the Power Cell is an advanced VRLA lead acid battery.

The following sections provide technical detail on the three main types of grid-scale battery technologies: Lead Acid, Lithium Ion, and Molten Sodium.

LEAD ACID BATTERIES

Lead Acid batteries were the first rechargeable battery put into commercial use, having been invented in 1859 by the French physician Gaston Planté [11]. They are a mature technology in widespread commercial use in automobile, UPS, and battery backup systems for telecom and other industries. Lead-acid batteries are the lowest cost batteries on the market today for grid applications, with MW scale projects having

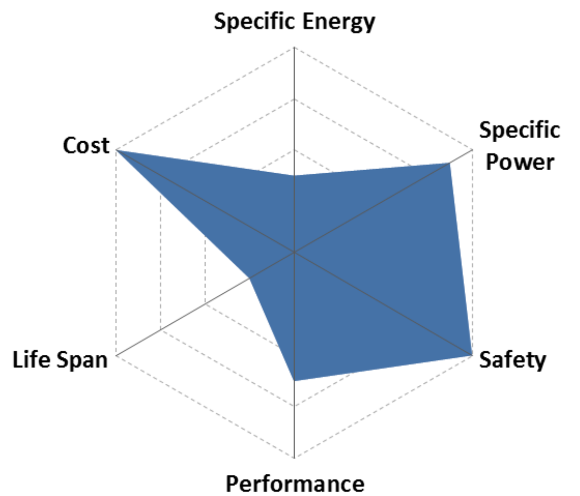

Figure 4: Lead-Acid battery spider-web plot. There are many lead acid battery variations, this chart is specifically for the Xtreme Power PowerCell

operated in various locations since the 1980's [12-14]. They are capable of delivering high power, depending on the cell design, and are relatively safe, with the national fire code not requiring dedicated fire suppression systems for large lead-acid batteries. Their downside is relatively short cycle life (200-1000 cycles to 100% depth of discharge), and their extremely high weight due to being made largely of lead, one of the heaviest non-rare metals on the periodic table.

Principle of Operation

Lead acid batteries operate according to a formation reaction on its plates. When fully charged, the battery consists of a negative plate (anode) of pure lead, a positive plate (cathode) of lead dioxide, and an electrolyte consisting of sulfuric acid dissolved in water. As the system discharges, electrons are driven from the positive to the negative plate as the sulfuric acid combines with the lead plates, forming lead sulfate on the surface of both plates according to the following reversible chemical reaction, where the electrons are flowing to the plates through an external circuit [11].

Negative electrode: $Pb + HSO4 \rightarrow PbSO_4 + H^+ + 2e^-$
Positive electrode: $PbO_2 + HSO4 + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

Total reaction: $Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

Figure 5: Graphical representation of lead acid chemistry when fully charged (left), and fully discharged (right)

Strengths and Weaknesses

Note that lead sulfate ($PbSO_4$) is an electrical insulator with a hard crystalline structure. With that fact in mind, examination of this chemical reaction suggests the major shortcomings of lead acid battery performance. As the battery gets discharged, lead sulfate builds up on the surface of the plate and acts as a barrier to additional reactions occurring. This causes electrical resistance to increase, generating heat due to I^2R losses, and reducing the system's efficiency. When the system is recharged the lead sulfate molecules are broken up and dissolved back into the electrolyte, which is not a perfect process and results in some degradation of the lead plates each time. For this reason, cycle life is short compared to some other chemistries [15].

Additionally, the lead sulfate crystals harden on the plates if the system spends a long period of time discharged, accelerating the degradation of the battery if it is not kept at full charge. Some battery applications require continuous operation at a mid-range state of charge so that the battery can either accept or deliver energy on short notice as needed, a duty cycle referred to as Partial State of Charge (PSOC) operation. Such a duty cycle may quickly wear out a lead acid battery if care is not taken [16].

Connecting lead acid batteries in parallel is also problematic due to the electrical resistance property of lead sulfate. If two batteries are connected in parallel and one has more charge than the other, the one with higher charge has lower internal resistance, and will therefore receive a higher percentage of the charge current than its neighbor. Ultimately the result is that either the high charge battery gets overcharged, thus reducing its life, or the lower charged battery never gets fully charged, thus reducing its life, or both in the worst case [17]. In order to prevent this from happening, the project may require regular downtime for equalization, as well as a larger operations and maintenance budget than with other choices of chemistry.

Despite these shortcomings, lead and sulfuric acid are cheap and plentiful materials, and the manufacturing process is mature and well understood. Lead acid batteries are so much less expensive than their competitors that even with multiple replacements the system can still be cheaper on a life-time cost of ownership basis than a longer lasting chemistry. When sized correctly in certain applications, lead-acid lifetimes over 10 years can be achieved [14].

Recycling of lead acid batteries is also a significant advantage, with one of the most successful recycling programs in the world. 96% of all battery lead is recycled, and 60-80% of the lead in a typical new battery is from recycled materials [18].

LITHIUM ION BATTERIES

Lithium batteries were first built in 1979 by John Goodenough and K Mizushima at Oxford University [19]. Early rechargeable lithium batteries suffered from poor cycle life and safety issues. Developments in Lithium Cobalt Oxide batteries with carbon negative electrodes at Sony in 1990 launched the modern era of ubiquitous lithium-based batteries in consumer applications[20]. Since then they have rapidly grown into a multi-billion dollar industry with applications in consumer electronics, power tools, electric vehicles, and are becoming increasingly popular in grid-scale storage.

Many people tend to assume that there is just one type of lithium battery, when in fact the term describes a family of dozens of different technologies, each with its own advantages and disadvantages. In general, the batteries move lithium ions between a positive electrode structure consisting of a lithium and transition metal compound and a negative electrode material usually made of carbon. The reaction is an insertion reaction that inserts lithium ions between layers or into interstitial sites on the electrode, and does not degrade the chemical structure of the electrodes on charge/discharge as with lead-acid batteries, resulting in much longer cycle life [21].

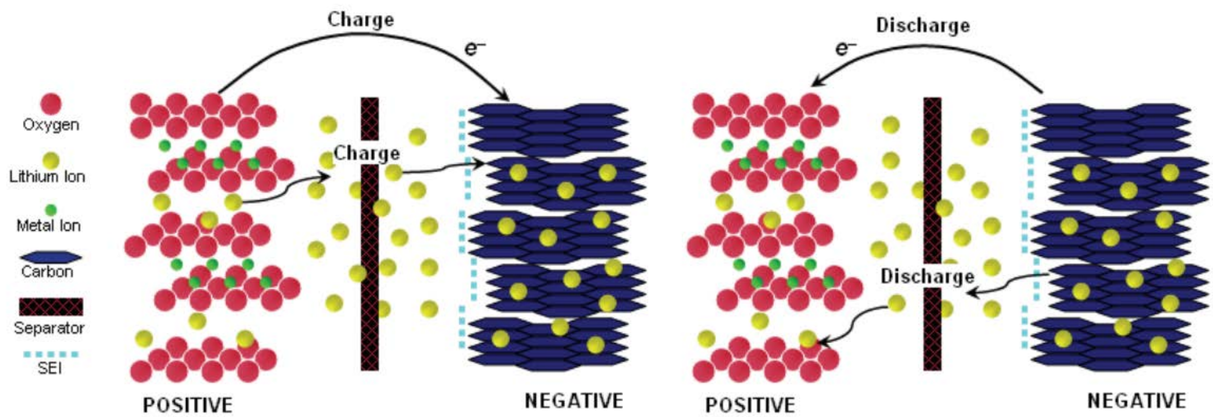

Figure 6: Representation of Lithium Ion reaction mechanism. [21]

The illustration in Figure 6 shows the structure and operating mechanism of a lithium battery with a graphite (C_6) negative electrode. Lithium ions are intercalated (inserted) into available sites in the crystal structure of either the positive or negative electrode, associated with an equal number of electrons flowing through the external circuit. The figure shows a Solid-Electrolyte Interface (SEI) layer on the surface of the carbon negative, which was Sony's technology enabling breakthrough. The SEI layer forms on the negative the first time the battery is charged, preventing uncontrolled reactions between the negative and the electrolyte [22].

Lithium batteries have two major risks that must be mitigated either by materials choice, cell design, or design of the system and enclosure. These risks are overheating, which principally affects the negative electrode, and overcharge, which is associated with the positive. Breakdown of the SEI occurs at around 110 °C, resulting in an uncontrolled reaction known as thermal runaway. The uncontrolled reaction takes between the negative electrode's lithium ions and the electrolyte, often resulting in a fire [22]. Depending on the choice of positive electrode material, the results of thermal runaway can vary greatly, with Nickel and Cobalt based batteries releasing far more energy to the environment in the worst case scenario, as indicated in Figure 7.

The other major safety hazard with lithium batteries can come from overcharging the battery, which pulls so many lithium ions from the cathode that the crystal structure becomes unstable. Some positive electrode materials (LMO, LFP) are inherently resistant to this phenomenon thanks to their voltage characteristics having a fast rise once the battery becomes full, which prevents the charging electronics from forcing in any more current. Batteries without this voltage characteristic require external circuitry to prevent a potentially destructive overcharge (NCA, LCO, NCM, etc.).

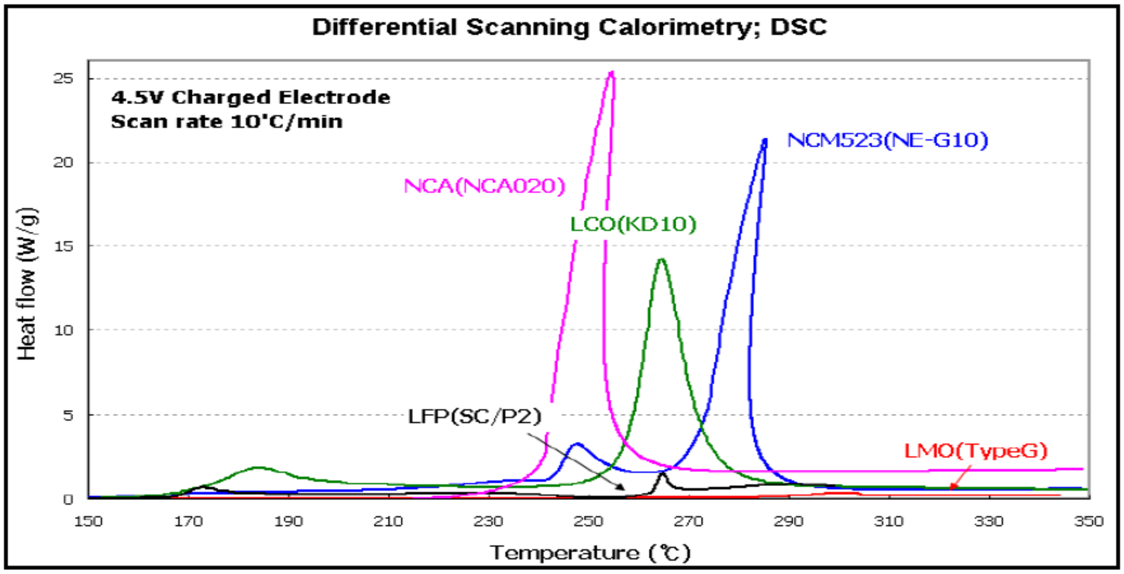

Figure 7: Heat dissipation during thermal runaway for various Lithium chemistries. Source: Samsung SDI

In grid-scale storage, lithium batteries with lower density, longer life, and inherent safety are typically chosen over those types common in handheld electronics with higher energy densities. The leading lithium types in grid-scale storage are Lithium Manganese Oxide (LMO), Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Lithium Titanate (LTO) batteries. Each of these is briefly discussed below.

Lithium Manganese Oxide (LMO)

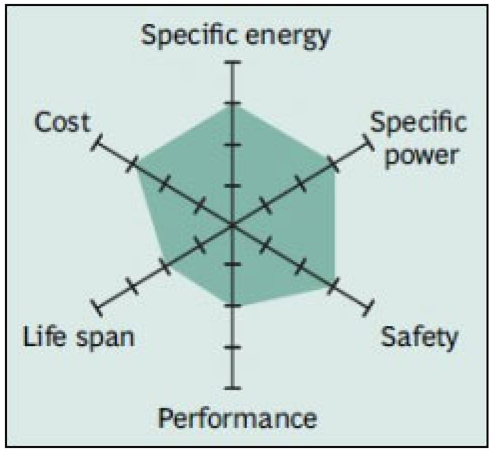

Figure 8: LMO spider web plot

Lithium Manganese Oxide ($LiMn_2O_2$, commonly called LMO) positive electrodes are often referred to as spinel-type, in reference to their crystal structure. These batteries have good inherent safety features, with a voltage characteristic that naturally prevents overcharge of the battery. Their main drawback is that Manganese spinel crystal is soluble in the electrolyte, resulting in Mn crystals migrating from the electrode and forming on the SEI layer, which locally prevents lithium ions from entering/leaving the negative [21]. Early LMO batteries exhibited severe capacity fade as a result of this process, but improvements in cell design have mitigated this somewhat, and commercial LMO batteries are now commonly rated for 4000 cycles [23]. Samsung SDI is the leading manufacturer of LMO batteries for grid applications.

Lithium Iron Phosphate (LFP)

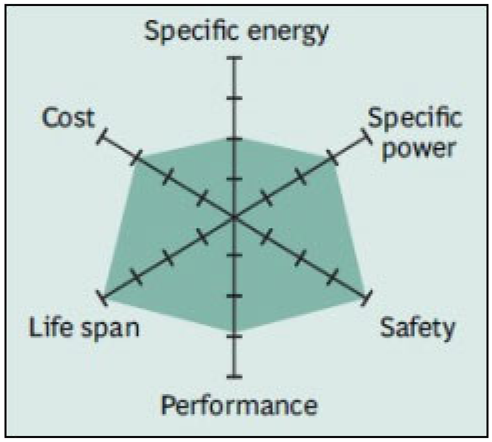

Figure 9: LFP Spider web plot

Lithium Iron Phosphate ($LiFePO_4$, commonly called LFP) electrodes were developed by Dr. John Goodenough's team at the University of Texas. Goodenough's team chose LFP for a positive electrode material because phosphate bonds are stronger than those in oxide materials [24]. The result is that the material releases very little energy on overcharge, or under conditions such as short-circuits, punctures, etc. The safety improvement comes at the expense of reduced energy density. A123, a battery start-up spun out of an MIT laboratory, has been the leading developer of LFP systems for the grid and other applications, but recently went bankrupt and was sold to a Chinese company. While that company's future is uncertain, the technology will likely continue to grow in popularity as a result of its inherent safety and long life, especially in grid-tied applications where energy density is not a primary concern of designers. Other leading manufacturers of LFP batteries include Korea's LG Chem, and China's CALB.

Lithium Nickel Cobalt Aluminum Oxide (NCA)

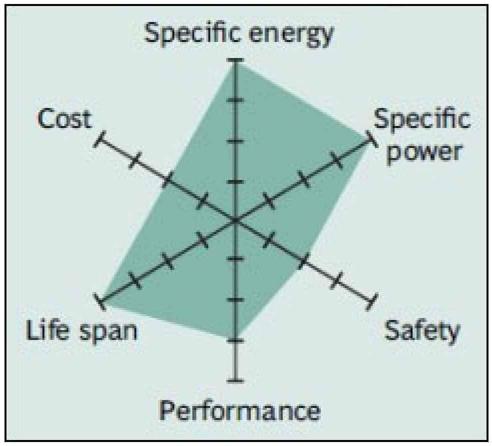

Figure 10: NCA spider web plot

NCA batteries are made from a mixture of lithiated nickel, cobalt, and aluminum oxides, of varying chemical proportions depending on the choices of the manufacturer. These materials have lower solubility of their crystals than LMO or Lithium Cobalt alone, which results in less damage to the SEI over time, leading to improved cycle life. While the material is generally considered safer than $LiCoO_2$, it does not have any of the beneficial safety characteristics mentioned above for LMO or LFP. As a result, safety is relatively poor, and many designers of battery systems for grid-scale applications are not comfortable with building large systems with them. The French company SAFT claims to have answers for the safety issues, and is promoting NCA for use in grid-scale applications around the world [21].

Lithium Titanate (LTO)

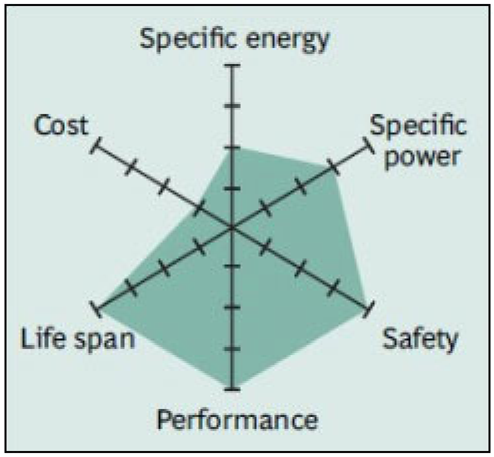

Figure 11: LTO spider web plot

Unlike the previous materials, Lithium Titanate actually refers to the negative electrode material, which is used in place of carbon. It can be paired with any of the positive electrode materials discussed above, which would be selected for their own desirable properties [25]. LMO is a common choice for a positive material paired with LTO. Lithium titanate operates at a less negative voltage with respect to the electrolyte, and therefore forms no SEI. As a result, none of the overheating or capacity fade issues that are associated with SEI degradation afflict LTO batteries, and they exhibit best-in-class safety under the widest range of conditions. LTO batteries can also be charged at extremely high currents (in as little as 5 minutes), and can have lifetimes anywhere from 2-10x as long as a battery with a graphite anode [26]. The tradeoffs are much higher material cost and complexity compared with graphite, and the lower operating voltage (comparable to that of a Lead Acid cell) results in lower energy density. Due to their high cost, these batteries are not as common in consumer applications as others, and their low density is undesirable in electric vehicle applications. As such, high power grid-tied systems may be the breakthrough application for LTO. Their major manufacturers are Toshiba and Altair Nanotechnology.

SODIUM-BETA HIGH TEMPERATURE BATTERIES

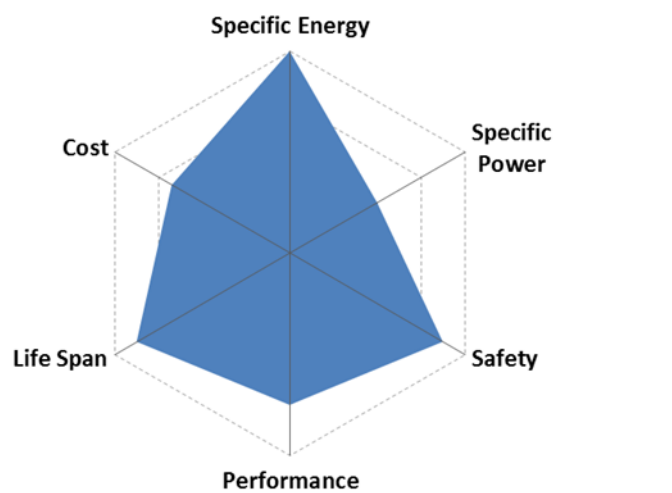

Figure 12: Sodium-beta battery spider web plot

Molten sodium-based batteries are the most widely deployed BESS technology in the world, mostly in the form of Sodium Sulfur batteries manufactured by the Japanese company NGK under the NAS trade name [27]. The other major type of Sodium-β (Sodium beta) battery use in large scale energy storage is Sodium Nickel Chloride (NaNiCl2), often referred to as the ZEBRA battery based on its roots in the Zero Emission Battery Research Activities group in South Africa [28]. These batteries were originally intended for transportation applications such as electric trains, but are being commercialized in electric grid applications by General Electric under the Durathon trade name, and the Italian company FIAMM, who refers to the product as SoNick.

Both types of Sodium-β batteries consist of two molten-metal electrodes, typically operating in the range of 270-350 °C, which are separated by a solid beta-alumina (β”-Al_2O_3) electrolyte. At this high temperature, positive sodium ions are ionically conductive through the ceramic electrolyte, while the other atoms cannot permeate it. As such, the battery is 100% coulombically efficient on charge, meaning that there is a 1:1 ratio between electrons flowing into the terminals and sodium ions contributing to increased state of charge [28]. This efficiency is not as big of an advantage as it may appear to be however, because the additional heaters and electronics that are required to get this battery up to operating temperature are considerable, and detract from the total round-trip energy efficiency of the BESS as viewed from the end user’s perspective. State of Charge estimation is much easier for this battery than for most, because current integration works perfectly if sensor noise is not biased.

Both Sodium Sulfur and Sodium Nickel Chloride batteries exhibit high energy density, but have very low power ratings compared with most Lead Acid or Lithium batteries. NGK’s NAS battery has a 1:8 power to energy ratio, while the GE Durathon battery has a 1:2 ratio, corresponding to maximum C rates of C/8 and C/2, respectively. Cycle life is comparable to high quality lithium batteries at 4500 cycles to 80% depth of discharge, and calendar life is excellent, with almost no shelf-degradation and expected lifetimes of 20 years.

To summarize, molten sodium batteries exhibit excellent energy performance, long duration, good safety and cycle life. Their principle detractors are limited power (low current per cell), poor self-discharge, and the special thermal management required for their operation. They are considered the best choice for many applications with durations over 2 hours, where they must be competitive with Compressed Air Energy Storage (CAES) and pumped hydro technologies as opposed to other electrochemical storage technologies.

Power Conversion System

The most critical element in integrating battery energy storage systems to the grid is the bi-directional inverter, or Power Electronics Conversion System (PCS). These units convert the varying voltage DC power from the batteries to a constant voltage AC power flow either to or from the grid depending on whether the unit is charging or discharging. There are two common architectures for the PCS, both of which feature a six, twelve, or eighteen pulse DC to AC conversion stage using such power electronics devices as IGBTs, GTOs, power MOSFETs, etc. The differentiator in the two architectures is the optional inclusion of a DC boost stage and regulated DC or AC link, using a capacitor/inductor for intermediate energy storage, as opposed to allowing the inverter to operate directly on the varying DC voltage of the batteries. The key trade-off between the designs is control complexity versus component cost. Both designs can achieve operating conversion efficiency of over 95%.

Both designs use Pulse Width Modulation (PWM) to control the switching of the power electronic devices [29], and require an AC filter stage to achieve a smooth sinusoidal output; typically LCL type filter stages are used, discussed in [30].

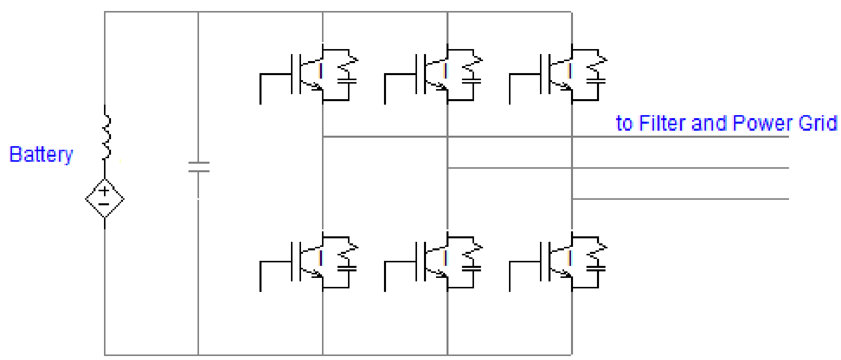

Figure 13: 6-Pulse converter with IGBTs. Converts battery DC voltage to 3-phase AC for the power grid

The more straightforward hardware implementation of the PCS is to convert directly from the varying DC stage to the constant voltage AC grid, as in the simple schematic shown in Fig. 13. Steady output is achieved by using voltage feedback to vary the magnitude of the modulation signal. One downside of this is that the DC voltage must always be kept above the product of the modulation signal magnitude and the AC output voltage. This creates a hard lower limit on allowable DC voltage. It is desirable to have high voltages on the AC side, so as to minimize the size of current carrying conductors needed and keep losses down. Building a very high voltage battery system means connecting many cells in series, and creates challenges with battery management, as well as adding expense to the components used on the battery pack, which must be rated for high voltage isolation.

Most of the real-world applications of a BESS are concerned with steady-state real and reactive power (P and Q) output of the inverter, taking place over time spans ranging from 100s of milliseconds to minutes or hours. Since the switching frequency of most grid-tied inverters takes place at speeds greater than 1kHz, it is desirable to separate the power electronics controls that determine P and Q needs from the DSP that actually controls the switching of the IGBTs or other power electronics devices used in the inverter. Controls will be discussed in the next section.

Other PCS design and selection criteria include their method of cooling, the environmental ratings of their enclosure and cooling equipment, and various international standards that the unit must be in compliance with. The power electronics switches as well as any magnetic components such as the inductors of the output filter generate considerable heat while operating, and this heat must be removed from the BESS. This can either be done using fans and forced air cooling, or liquid to air heat exchangers that work much like the radiator on a car. Forced air cooling occupies much more space than liquid to air, but the latter requires the use of various pumps and fans, adding complexity and reducing system reliability as a result. If the unit is outdoor rated the enclosure must be rated to Nema 3R or 4X levels, providing protection against ingress of water and foreign materials. Nema 4 units are designed to be un-harmed by a variety of foreign materials in the atmosphere, must be corrosion resistant, and should be undamaged by the external formation of ice on the enclosure [31]. These requirements are especially important in remote locations such as Hawaii and Alaska, which may be subjected to nearby volcanic activity and severe weather on a routine basis.

There are many standards that may be applicable to a grid-tied PCS governing their electrical and safety characteristics. These include IEEE 1547 and UL 1741 standards for distributed energy resources, which govern such issues as anti-islanding and voltage and frequency ride-through requirements [32, 33]. The quality of output power is usually specified to be within the limits stated in the IEEE 519 standard, which requires that THD and all harmonics be less than 5% of the nominal frequency component [34]. Systems must also be shown to be compliant with CE safety codes, the National Electric Code, and occasionally certain EMI and acoustical noise requirements, which are usually dictated by the customer.

Control Systems

Large battery storage systems must strike a balance between accomplishing the overall goals of their intended application, while simultaneously making sure that all system components are operated safely within their design parameters (typically voltage, current, and temperature related), and controlling battery charge/discharge such that the battery lifetime is as long as possible, and operations and maintenance costs are kept to a minimum. In order to meet all of these requirements, several layers of measurement, state estimation, and feedback between devices are needed to meet these goals.

The functional blocks of the control system can be separated into a Battery Management System (BMS), a PCS Unit Controller, and a Plant Master Controller. These blocks are depicted in Figure 14 below, next to the physical components of a BESS that they are responsible for interfacing with. The different functions may be instantiated as different application threads in a single industrial computer for simple systems, or can be broken out into several discrete devices communicating over cables or optical fibers in larger, more complex systems. Each of these functional blocks is described below.

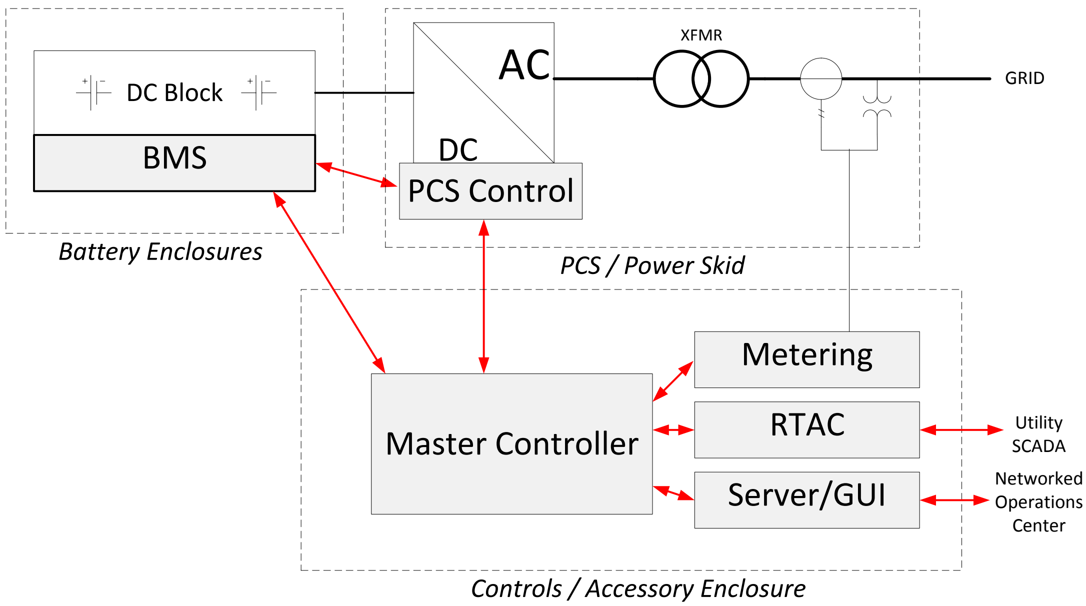

Figure 14: Example control system architecture diagram for a grid-tied BESS. Red lines show flows of information between devices.

Battery Management System

The name BMS refers to either a Battery Management System or a Battery Monitoring System, depending on whether it has any control functionality or not. The exact requirements of the BMS depend on the battery itself, and most manufacturers of grid-scale batteries have developed a BMS in house that is tailored to the needs of their battery [35, 36].

BMS functions - Monitoring

Regardless of the battery, all BMSs will measure voltage, current, and temperature for the battery pack as a whole, as well as individual cell or module voltages, currents, and temperatures as necessary.

BMS functions – SOC and other parameter estimation

The BMS will use these measurements to calculate or estimate various other important parameters needed for battery operation [36, 37]. These estimated parameters include:

- State of Charge (SOC): the energy stored in a battery as a percentage of its maximum or rated energy capacity.
- State of Health (SOH): the energy storage capacity of a battery, usually as a percentage of its rated capacity when new. SOH will steadily decline over the life of a battery, and when it gets low enough the battery must be replaced.
- Real-time operational limits such as:
    - Maximum instantaneous charge/discharge power
    - Maximum instantaneous charge/discharge current
    - Maximum instantaneous charge/discharge voltage
- Time or cycles until the next required maintenance charge or inspection

Parameter estimation is a critical function, particularly for State of Charge. If the SOC is not accurately known then it is possible to accidentally run out of energy too early on a discharge, or to accidentally overcharge the batteries, both of which will result in poor performance of the system from the operator or customer's perspective. In practice it can be very difficult to accurately SOC over the course of many hours of operation due to the following challenges:

- Sensors are imperfect, with noise and calibration issues affecting measurement and calculation
- Conversion efficiency of DC power into stored energy is imperfect, and is a variable function of such parameters as SOC, SOH, Temperature, Battery Internal Resistance, etc.

As a result, there are many approaches to SOC estimation in the literature, and this continues to be an important area of R&D for companies making BMS equipment. References [38] and [39] present overviews of the state of the technology, and the tradeoffs of various approaches.

BMS functions – Battery balancing

Microscopic differences between batteries will result in different charge efficiencies and self-discharge rates, and over time this means measureable differences in SOC. When many batteries are connected in series, it is important to maintain each cell at a similar SOC to those around it, because overcharge or over-discharge can destroy a battery's life and possibly be a safety hazard. Therefore, the usable discharge capacity of a string of series batteries is equal to that of the battery with lowest SOC, and the charge capacity is equal to that of the battery with highest SOC. Maintaining equal SOC across a string of batteries is referred to as battery balancing. Figure 15 shows the effect of battery imbalance on the usable capacity of the system.

Some batteries can accept a sustained overcharge without being harmed, especially those with aqueous electrolytes and water-based reactions, and these batteries can be balanced using a prolonged maintenance charge that equalizes all batteries at 100% SOC. For most lithium and some lead acid batteries this is not a safe approach, and battery balancing circuitry must be integrated into the BMS. Balancing circuits fall into two categories, Passive and Active [36].

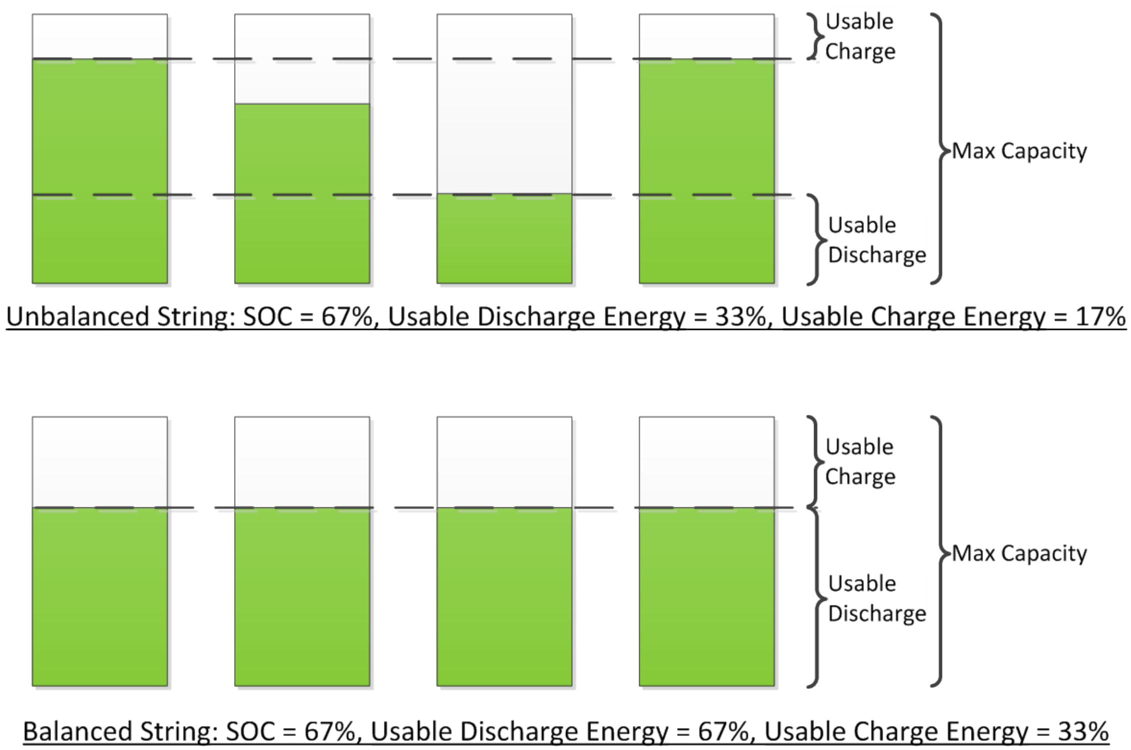

Figure 15: Illustration of battery balancing. Note that at the same SOC, the balanced system has twice the usable capacity.

Passive Balancing – uses a shunt resistor switched into contact with the electrodes to discharge the batteries with high SOC, down to the level of their neighbors. This is the most simple and low-cost method of balancing, and is very widely used. The tradeoff is that stored energy is dissipated into heat, which reduces system efficiency and can negatively impact the system economics [36].

Active Balancing – using switches and simple power-electronic devices, energy can be moved with modest losses from batteries with high states of charge to other batteries in the string with low states of charge. This approach results in improved efficiency, less heat dissipation in the system, and in some cases it can result in faster balancing of an unbalanced system. The tradeoff is increased system cost and complexity. A good background on active balancing methods can be found in [40] and [41].

PCS UNIT CONTROLLER

As discussed in the PCS section above, the PCS is a power electronic device that converts DC to AC power resulting in energy flows that charge and discharge the batteries. A PCS Unit controller is required to control the DC Charge and Discharge currents while simultaneously delivering the desired Real and Reactive Power flows on the AC side.

In large, distributed systems, this device will directly interface with both the BMS and the Master Controller, as well as the PCS gate-drive electronics. Feedback from the BMS will inform the PCS Unit Controller how much power the battery can accept or deliver. Measurements from inside the PCS will indicate whether the system is operating properly, and if any de-rating is required due to high temperatures or cooling loop issues. The PCS Unit Controller will calculate its range of real/reactive AC power capabilities from all of this information, and feedback to the master controller enough status information for it to intelligently allocate power requirements among available PCSs.

SYSTEM MASTER CONTROLLER

A centralized master controller is responsible for the overall performance of the system. It communicates with all PCS Unit Controllers, possibly all BMSs, the utility Supervisory Control and Data Acquisition (SCADA) system, the operator, any external metering equipment, and possibly the control equipment for nearby wind, solar, or diesel generators. The master controller is referred to by various terms in the industry, such as Energy Management System, Power Management System, Plant Controller, etc.

The master controller functionality includes communication with many devices, and a set of real-time control algorithms that determine the commands for each PCS in the system. These control and communication algorithms can be run on a wide range of hardware, from industrial PCs to embedded microcontrollers, to traditional PLC hardware. To date there is very little standardization in the industry on system control hardware and software, with each of the major battery manufacturers having their own proprietary system, or contracting with companies such as Xtreme Power to obtain one. Several start-ups have recently entered this space, hoping to provide a software solution to the control of battery energy storage systems, without needing the large capital costs involved in manufacturing batteries or MW-scale power electronics [42-44]

Balance of Plant

In addition to the batteries, controls, and power conversion system, a variety of other equipment is required in a grid-scale BESS. This equipment is referred to as the Balance of Plant (BOP), and includes the enclosures that house the equipment, HVAC equipment for maintaining desired operating temperatures, as well as pumps, fans, and heat exchangers for any liquid cooling loops in the system. These considerations are often handled by mechanical or industrial engineers, and are also critical to the success of the system. These services are sometimes handled by the BESS designer, but may also be outsourced to traditional power system engineering procurement and construction firms such as Power Engineers, Fluor, and others.

III. GRID-SCALE BESS APPLICATIONS & CONTROLS

Overview

Several large-scale research projects have been conducted to determine possible uses and value streams for grid-scale energy storage. An excellent overview was published in 2010 by Jim Eyer and Garth Corey, researchers at Sandia National Labs [45]. The report discussed 17 possible applications for grid-scale energy storage, and gave estimates of the financial benefit for each mode of operation. Similar efforts were undertaken by the Electric Power Research Institute and the Department of Energy, resulting in the EPRI-DOE Handbook for Energy Storage in T&D Applications [46].

The Hawaiian islands have been one of the most active areas for battery energy storage development, thanks to a combination of an aggressive renewable portfolio standard, small, isolated electricity grids, and the high cost of diesel fuel which must be brought to the islands on a boat. More than 10 large storage projects are in operation or development in Hawaii. Sempra, the parent company of San Diego Gas & Electric, conducted a thorough study of the market in preparation for their development of the Auwahi Wind Farm and Battery Storage project on the island of Maui [47]. That report included figures 16-18 below. Figure 16 shows the approximate size range in power (X-axis) and duration/energy (Y-axis) of the various key applications for energy storage identified in the Sandia report and elsewhere. Figure 17 shows the companies active in the grid energy storage market as of late 2011, divided according to company size and the degree to which grid-scale energy storage is their key area of focus. Figure 18 shows the power, energy, technology, and commissioning date of all of the major battery energy storage systems deployed in the United States in the last 10 years.

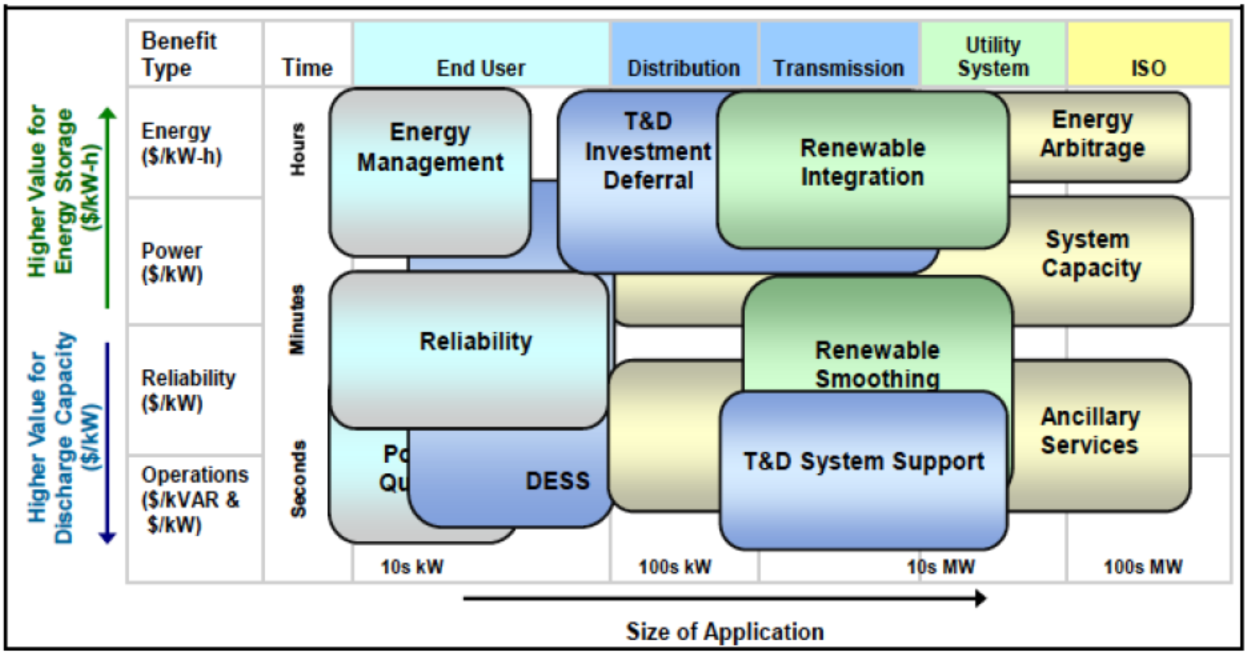

Figure 16: Graphical representation of the power and energy requirements of some of the major applications for grid-scale battery energy storage systems. Source: Sempra

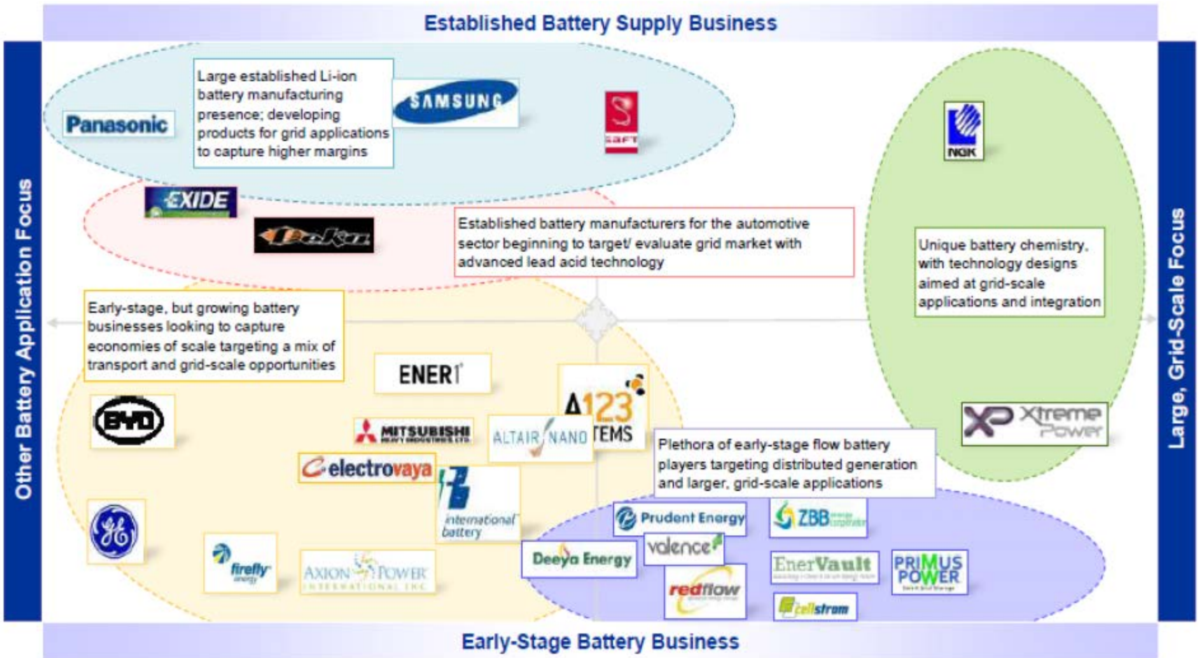

Figure 17: The major players of the grid-scale battery energy storage business, circa November 2011. Larger companies are placed higher up. Those whose business focus is targeted at grid-scale storage are to the right, while companies focused on other battery applications are to the left of the graph. Source: Sempra

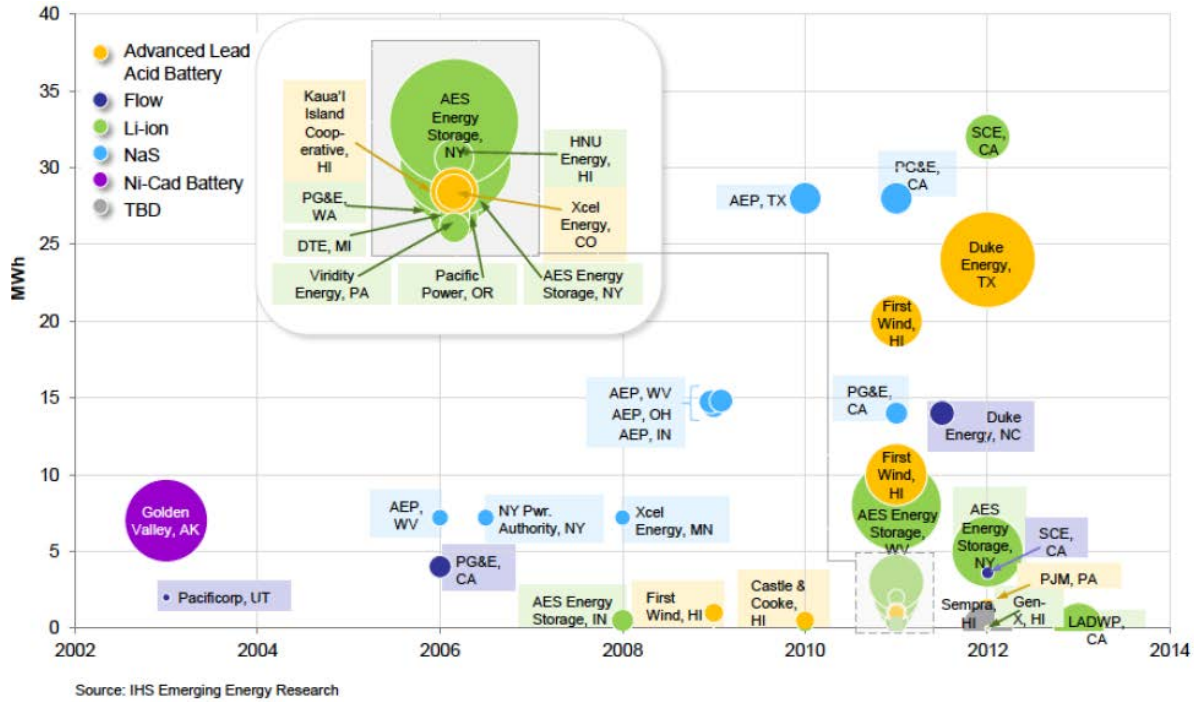

Figure 18: A graph depicting the power rating (circle diameter), energy capacity (vertical placement), technology (color), and commissioning date (horizontal location) of all of the major battery energy storage systems deployed in the United States in the last 10 years.

This section of the report presents details of the most widespread uses of grid-scale BESSs, and presents the fundamentals of the control algorithms that must be implemented on the BESS master controller. Additionally, it has been mentioned that no single battery technology is appropriate for all applications. When developing a BESS for an application, it is important to look at the expected duty cycle to determine how many MW for what duration are required in order to size the system with a cost effective solution. Other considerations such as the target state-of-charge and battery cycle life must also be weighed. Each application below will list the battery technologies from

Section II of this report that are likely to be appropriate choices. Figure 19 expands the battery versus cost effective duration chart given in Figure 3 to include application duration requirements.

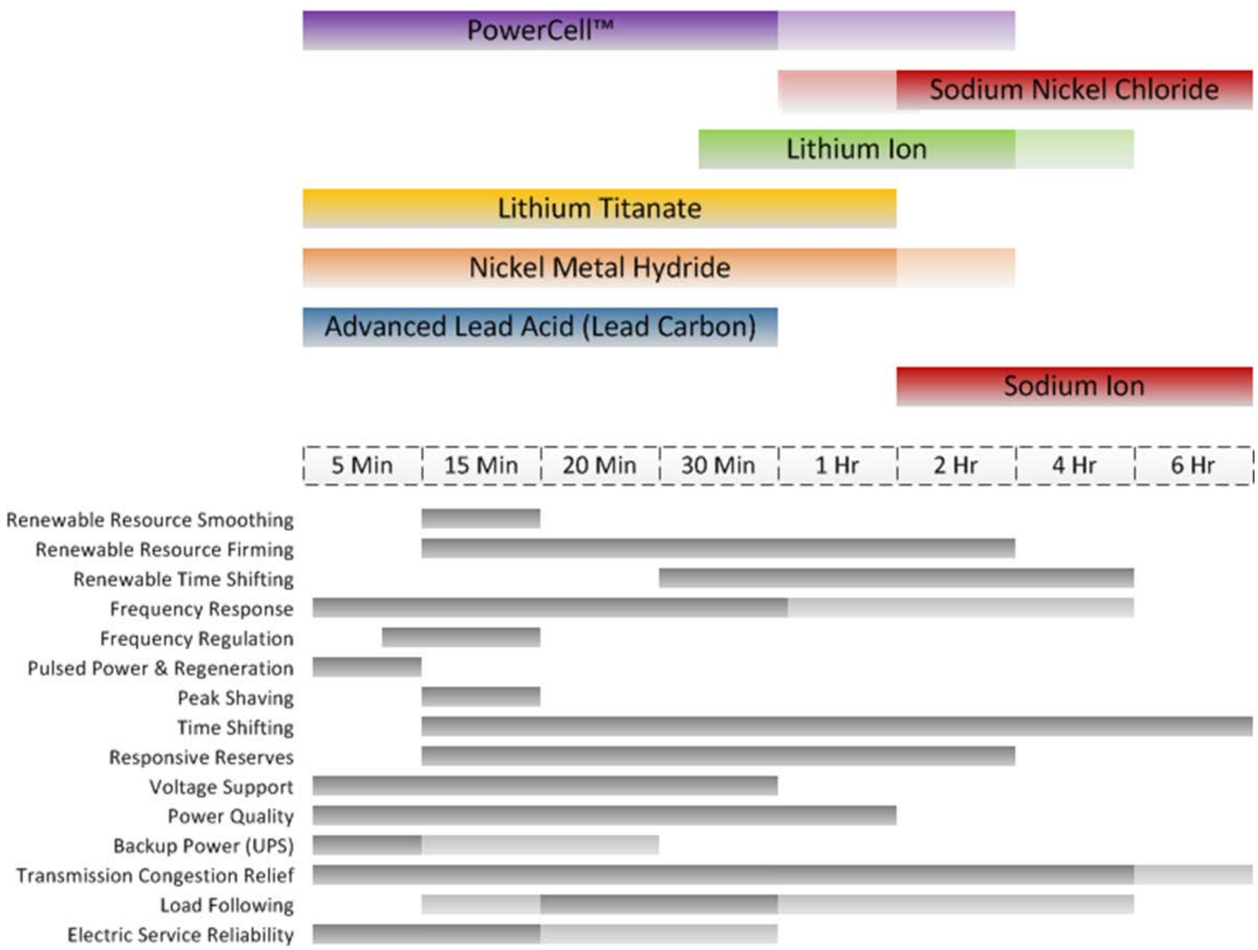

Figure 19: Expansion of Figure 3 to show battery chemistry optimal durations mapped to the duration requirements of various grid-scale BESS applications. Source: Xtreme Power, IEEE Presentation 2012

Frequency Response

In AC power systems, it is essential to maintain the system frequency close to the nominal frequency that the machines were designed for. The vast majority of systems around the world are designed for either 50 or 60Hz operation, and the traditional generating units of a power system will deliver AC power at exactly this frequency when power generation is perfectly matched to the load and system losses. When there is a load/generation mismatch, such as in the case of a generator suddenly tripping offline, the generators on the power system will give up energy stored in the form of rotational inertia in order to serve the power system load, and the result is that the machines slow down and frequency drops. In the case of a sudden loss of load the frequency will rise as the process plays out in reverse. Many devices on the power system can become damaged by prolonged operation outside of the nominal frequency range, and protective measures are in place on most power systems to shut down components automatically in the face of major frequency events, with the goal of avoiding a cascading blackout.

Small power systems such as those in remote locations, islands, and islanded microgrids have an especially large challenge maintaining frequency, as there are fewer rotating generators online, and the system therefore has less inertia. On small power grids it is not uncommon to see frequency deviations of 1-3 Hz from the nominal 50 or 60Hz frequency. Compare this to power systems in the continental United States, where many thousands of megawatts of generation are interconnected and 0.1 Hz deviation is considered very significant. As discussed above, frequency deviation is caused by a mismatch in generation and load, as governed by the swing equation for a Thevenin equivalent power source driving the grid. The system inertia is typically described using a normalized inertia constant called the H constant, defined as

$$H = \frac{stored\ kinetic\ energy\ at\ synchronous\ speed}{generator\ voltampere\ rating} \tag{1}$$

and H can be estimated by the frequency response of the system after a step-change such as a generation unit breaker trip. From the definition of H in [48], the equation can be re-written so that the system H is calculated from the change in frequency of the system after a generator of known size has tripped off, according to

$$H = \frac{\frac{1}{2}J\omega_s^2}{P_{post}} = \frac{1}{2}\left[\frac{-\Delta P_m}{d\omega_s/dt}\right]\frac{\omega_s}{P_{post}} = \frac{-\Delta P_m f_s}{2P_{post}\left(\frac{df_s}{dt}\right)} \tag{2}$$

where the unit of H is seconds, ω_s is system angular speed, f_s is the system frequency, P_{post} is the remaining generation online after the unit trip, and ΔP_m is the size of the generator that has tripped. The smaller the power system, the smaller the resulting H value, and the more the system frequency will be affected by a step change in generation or load. Note that the H value discussed here is for an entire power system, not an individual generator as it is in most electric machines textbooks.

In traditional small power systems, most of the generation consists of rotating machines running on diesel fuel, with considerable mass rotating on a shaft and contributing to H through the $\frac{1}{2}J\omega_s^2$ term of equation (2). With increased penetration of solar photovoltaics (PV) and generation technologies using power electronics to connect to the grid, it makes sense to conclude that some power systems could see their frequency stiffness and H values decline, making frequency regulation more difficult [49]. Utilities in the Hawaiian Islands and other remote locations have experienced this first hand, and the author has been fortunate to get to work on some of the first commercial BESS control systems to help regulate frequency in small power grids with high renewable power penetrations.

With this background motivation, an algorithm that mimics the governor of a generator equipped with a speed-droop regulation characteristic was developed at Xtreme Power for projects on the small Hawaiian Islands of Lanai [50] and Kauai [51], and is also now in use in modified form on Maui and Kodiak Island, Alaska. The system responds to measured deviations in frequency by delivering or absorbing power to stabilize the system, with a total response time less than 50ms.

Droop Response

Traditional AC generators typically come equipped with a speed governor with what is known as a speed-droop or regulation characteristic. This allows each generator on the grid to contribute to stabilizing the grid at the nominal system frequency, without the need for centralized coordination. Droop response in a governor is presented mathematically as a proportional controller with a gain of 1/R, where R is defined as

$$\% R = \frac{percent\ frequency\ change}{percent\ power\ output\ change} \times 100$$

$$\%R = \left(\frac{\omega_{NL} - \omega_{FL}}{\omega_0}\right) \times 100 \qquad (3)$$

where ω_{NL} is steady-state speed at no load, ω_{FL} is steady-state speed at full load, and ω_0 is the nominal or rated speed of the generator. As an example, a 5% droop response would result in a 100% change in a generator's power output set-point when the frequency changes by 5% (3Hz on a 60Hz power system) [52].

The simple implementation of this control scheme for a BESS is to compute a charge or discharge setpoint that is proportional to the difference between system frequency and its nominal value. Adding a deadband about the nominal frequency prevents the unit from unnecessary cycling throughout the day. The BESS response has units of kW and is given as

$$Response = \left(\left(\frac{f_{grid}-f_{DB}}{f_{DB}}\right)/\text{Percent } R\right) \times kVA_{BESS} \quad (4)$$

where f_{grid} is the grid frequency, f_{DB} is the frequency deadband, and kVA_{BESS} is the power rating of the BESS in kVA.

An example of BESS frequency response is presented in Figure 20, a snapshot of the BESS operator interface of the Xtreme Power designed BESS at the KWPII Wind Farm in Maui. This 30MW wind farm features a 10MW BESS that is designed to provide ramp rate control, responsive reserves that can be dispatched by the utility in emergencies, as well as direct frequency response. The frequency deadband for this site is 0.2Hz, and there are several small frequency events per day on average. A large event in Maui is depicted in Figure 20, where frequency is the black line, as measured by potential transformers at the 35kV substation, and BESS response with units of kW is the blue line as measured by the metering hardware on the BESS-side of the switchgear at the same substation. Here we see the frequency decline in response to a loss of generation on the island, with the controller responding immediately, delivering nearly

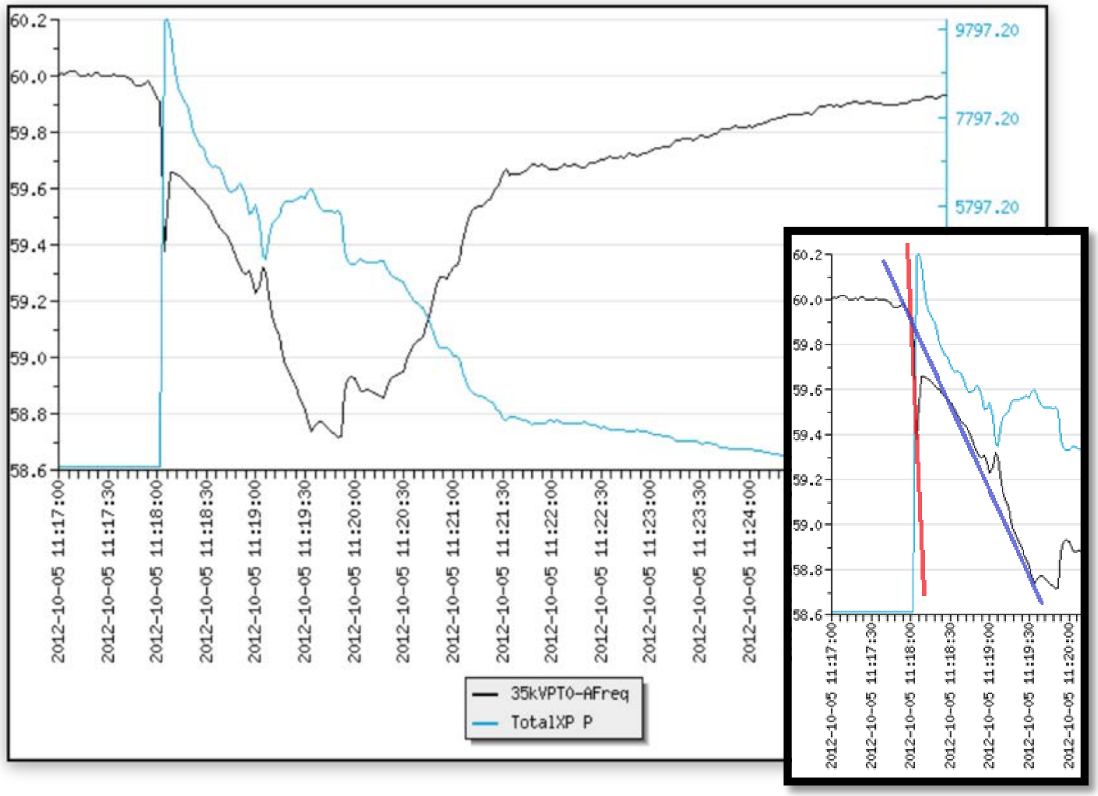

Fig. 20: (a) Frequency event with synthetic inertial response. (b) Detail of the same event with overlaid lines showing approximate before and after df/dt.

10MW of power less than one second from the start of the event. One can see that the frequency instantly recovers somewhat as a result, and the rest of the event features a lower *df/dt*, which from equation (2) suggests that this BESS and controller combination has effectively increased the island's H value for system inertia. To *df/dt* lines were added to the detailed view in Fig. 22 (b) to highlight this behavior.

The frequency response application has high power requirements and events with typical durations less than 10 minutes. At the present time, the most economical battery systems for this application tend to be based on lead-acid, and in some cases LTO will be an appropriate choice. Other lithium chemistries rated for 3C or higher power output may also be a good choice.

Frequency Regulation and Operating Reserves

In large power systems, there are more large generators contributing to system inertia, and frequency is maintained within a tighter band. In these systems, frequency regulation is maintained by a combination of local, automatic controls built into the governors of the various generators, called *primary frequency control* as well as through a centrally coordinated automatic control signal sent by the utility or an independent system operator (ISO), known as *secondary frequency control*. The signal sent to generators is generally known as Automatic Generation Control (AGC), and is typically updated every 4-10 seconds, depending on the system operator. With traditional technology in large interconnected systems, primary frequency control is what limits the magnitude of frequency deviation during an event such as loss of a large generator, while secondary frequency control is what restores the frequency back to its nominal value [52, 53].

In ISO territories, secondary frequency control is typically handled through an ancillary service market that runs along-side the real-time energy market, and deals with the fluctuations that occur in between the settling periods of the real-time market. This ancillary services market goes by different names depending on the ISO, but is usually just called Regulation, and takes the form of a Reg Up and a Reg Down signal, designed to push the frequency up or down.

In late 2011, the Federal Energy Regulatory Commission (FERC) issued Order 755, which requires that ISO's adopt a pay-for-performance compensation model for secondary frequency regulation [54]. This rule has had the effect of greatly increasing the compensation for resources that can respond to changing input signals with a high degree of speed and accuracy. Grid energy storage is literally unparalleled by conventional generation technology in this regard, with traditional generators taking as much as 10 minutes to reach a new AGC setpoint that would be achieved by a power electronics enabled BESS in less than 100ms, more than 6000 times as fast.

The first ISO to implement the pay for performance model for regulation was the PJM Interconnection, the nation's largest ISO serving over 60 million people in the country's Eastern half [55]. Their initial proof of concept testing was done on AltairNano's LTO batteries. The 32MW Laurel Mountain facility is the largest of its kind in that system, and was built by AES using $LiFePO_4$ batteries manufactured by A123. That facility recently surpassed 400,000 MWh of energy throughput in regulation service [56].

The Electric Reliability Council of Texas (ERCOT) has also launched a pilot project for fast responding frequency regulation services, although they are not under FERC jurisdiction as ERCOT operates entirely within the state of Texas. The first large battery system to participate in this project is the 36MW/15 minute Notrees Battery Storage Project in Notrees, Texas. The system was financed by Duke Energy and the

U.S. Department of Energy, and was built by Xtreme Power using an advanced lead acid battery technology. The Notrees system became operational in December 2012 [57].

When designing a BESS for Frequency Regulation, the duty cycle is typically very power intensive, with the system required to charge and discharge at its maximum power rating several times an hour for a few minutes at a time. This requirement limits the choice of batteries to high C-rate lithium batteries, and certain thin-plate lead acid battery designs. There are also some additional control requirements, as there is no guarantee that the AGC signal to be followed will be energy neutral, meaning that following the signal exactly will lead to either a completely full or completely empty battery which is incapable of participating in further regulation. As such, the system must analyze the current state of the system and determine how much to deviate from the AGC signal to maintain an appropriate SOC over time, while still meeting the performance metrics set forth by the ISO.

The initial implementation of the ERCOT fast frequency regulation market requires the BESS to follow AGC instructions throughout the day, updated every 4 seconds. In the case of severe events, defined as frequency excursions greater than 0.09Hz, the system temporarily stops following AGC, and instead delivers power at its maximum capacity. This behavior is depicted in Figure 22, where a major generator on the ERCOT grid went offline and caused frequency to drop to 59.85Hz. The Notrees BESS responded with over 28MW of power within milliseconds of crossing the 59.91 Hz threshold. The AGC signal caught up to the event roughly 10 seconds after it had begun.

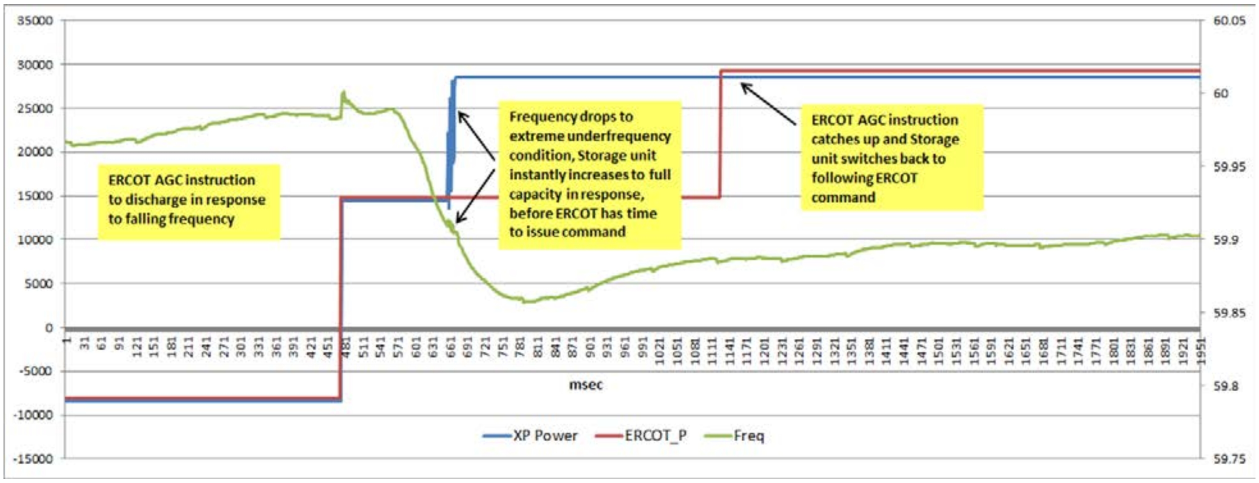

Figure 21: Frequency Regulation during a large frequency event on the ERCOT Fast Frequency Response pilot program. Source: Xtreme Power

Renewables Integration

The rapid growth of wind and solar power is a key driver in the adoption of grid scale battery energy storage systems, especially in regions with small power systems and remote areas. The chief difficulty with integrating significant quantities of wind and solar power into the grid is a result of the inherent variability of these sources. Fluctuations in output power of a wind or solar generator can cause frequency and voltage deviations on a grid. A BESS that is co-located with renewable energy resources can mitigate many of the challenges posed by these generation sources. Most often, the BESS controls for a renewable integration project will control ramp rates as well as offering frequency response. Voltage regulation and power factor correction are also common requirements. New systems are proposing to use storage to level the output of solar generators, offering the grid operator a firm resource during the day. Frequency response and regulation was discussed separately from renewables, because it can benefit any power system. The following control modes are always executed by a BESS with a master controller that can measure and respond to the output of a nearby generator, usually a wind farm or solar PV installation.

RAMP RATE CONTROL

On small power systems with high penetrations of renewable generation, intermittency can cause serious problems with power delivery, as traditional thermal units struggle to maintain the balance of power in the face of rapid changes. Solar photovoltaic (PV) generation facilities have no spinning inertial components, and the generated power can change very quickly when the sun becomes obscured by passing cloud cover [58], far faster than wind. This section presents ramp-rate control for solar power, but the principles apply to wind generation as well. During operation the BESS must counteract quick changes in output power to ensure that the facility delivers ramp rates deemed acceptable to the system operator. Allowable ramp rates are typically specified by the utility in kilowatts per minute (kW/min), and are a common feature of new solar and wind power purchase agreements (PPAs) between utilities and independent power producers.

Figure 23 depicts the operation of an Xtreme Power designed BESS smoothing the simulated volatile power output of a 1MW solar farm. The specifics of the algorithm

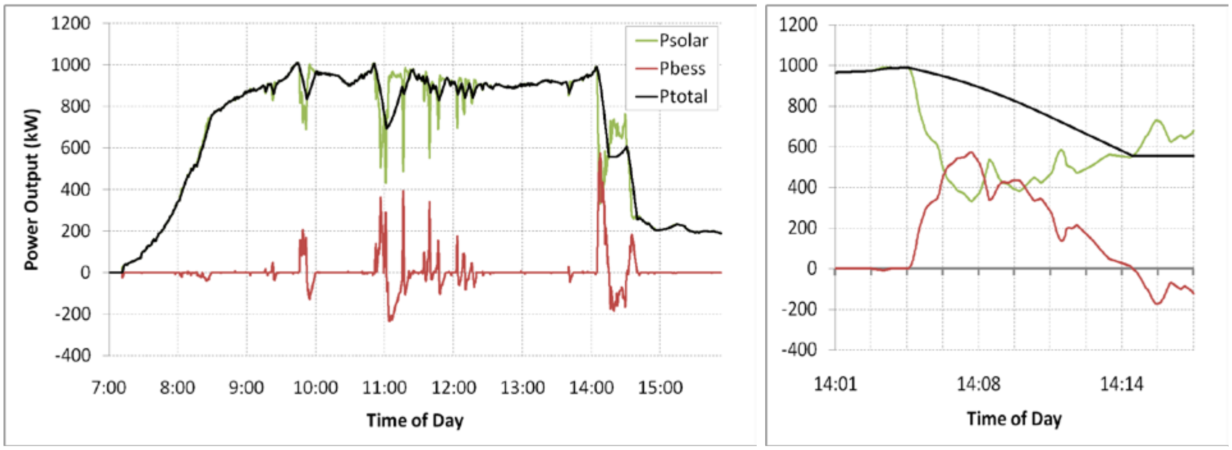

Figure 22: One full day of ramp control of solar PV (left),
detail of the largest event of the day (right).

are patented and proprietary to Xtreme Power [59, 60]. Note that the system ramp rate is maintained to less than 50kW/min, whereas the solar resource alone had a maximum second-to-second ramp rate of over 4 MW/min. This behavior translates to a significant reduction in wear and tear on the diesel generators supplying the rest of the grid, and helps the thermal units maintain power balance and the system electrical frequency. It is typically the case that the specifics of the thermal units on the system will be a major factor in determining the allowable ramp-rates for the PV asset. The economic value of smoothing and balancing services are discussed in [61]. Ramp-rate control is often also referred to as smoothing.

GENERATION FIRMING (LEVELING)

In addition to its uses in improving system stability through Frequency Response and Ramp Control, a BESS can also be used to improve the economic profile of the renewable generator to which it is attached. In some energy markets the ability to accurately schedule power generation ahead of time comes with significant economic benefits, either in the form of higher prices for the energy, or avoidance of penalties in the PPA.

In power systems where this is the case, BESS controls can be integrated with weather forecasts and market signals to deliver power at a consistent output level during set times of the day. Control logic on the BESS will use the battery to minimize deviations between scheduled and actual power output throughout the day. Figure 24 depicts results of a Solar Leveling application test at the Xtreme Power high-power test facility in Kyle, Texas [62]. Note that the total power output from the combined BESS and PV generation is maintained within a tolerance of ±10% of the power setpoint. Such behavior greatly improves the dispatchability of the PV resource, and it is thought that many markets will seek this type of functionality for renewables with BESSs in the future.

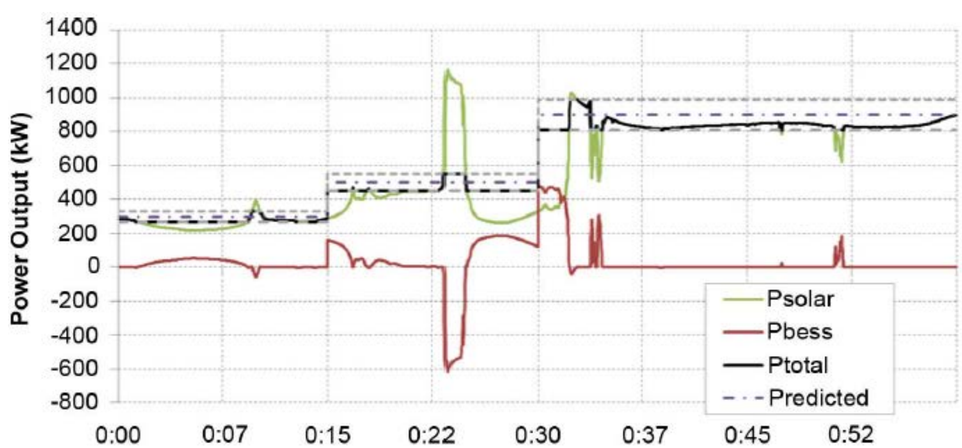

Figure 23: Solar Leveling application, where BESS maintains total system output to ±10% of a previously predicted value

TIME SHIFTING / ARBITRAGE

The economics of a renewable generator can be improved by shifting the energy delivery from the time it is generated to a later time where energy is more valuable. Time-shifting is a common application of pumped hydroelectric storage technology, the original grid-scale energy storage technology. Pumped hydro operates by pumping water to a higher elevation at night when energy is cheap or there is excess generation capacity available from must-run generators such as nuclear power facilities, and letting the water flow back down through a hydroelectric generator when energy is expensive. Using energy storage in this form transmits power across time in a way that is analogous to what the electric transmission system does across physical space. Pumped hydro technology is frequently sized in the range of hundreds of MW of rated power, and requires a very specific set of geological features to be feasible at a given site. The same basic application can be executed by a BESS control system anywhere on the grid.

When the system seeks to store and release energy from a particular generation source such as a PV farm, the application is commonly referred to as Time Shifting. The same control logic can also be run at any point on the power grid to try and take advantage of nodal price differences, and is referred to as Energy Arbitrage in this case. To date, energy arbitrage is far from profitable with battery energy storage, and this is detailed in a report by researchers at Sandia to evaluate possible use cases for a 32MWh energy storage system under construction in Tehachapi, CA for the Southern California Edison utility company [63].

Solar time-shift has been examined over the last year by Xtreme Power and Xcel Energy at the SolarTAC facility in Aurora, Colorado. The system at SolarTAC is a 1.5MW/15 minute lead-acid BESS, connected to a variety of prototype solar installations under test there. The results of a solar time shift test are presented in Figure 25. The system charges from some percentage of the solar generation during the day, and discharges as power output from the solar facility begins to drop off in the afternoon hours. The result is more energy delivered during the peak demand times in the day, which come in the late afternoon on most power systems. The economic benefit of the system running this control application is calculated by weighting the integral of power delivered by the energy prices throughout the day, and comparing the scenarios with and without solar time-shift. Also of interest to Xcel Energy in this demonstration project is the possibility of reducing congestion, line losses, and emissions from reducing "peaking" power plant generation if such technology were to become widespread [62].

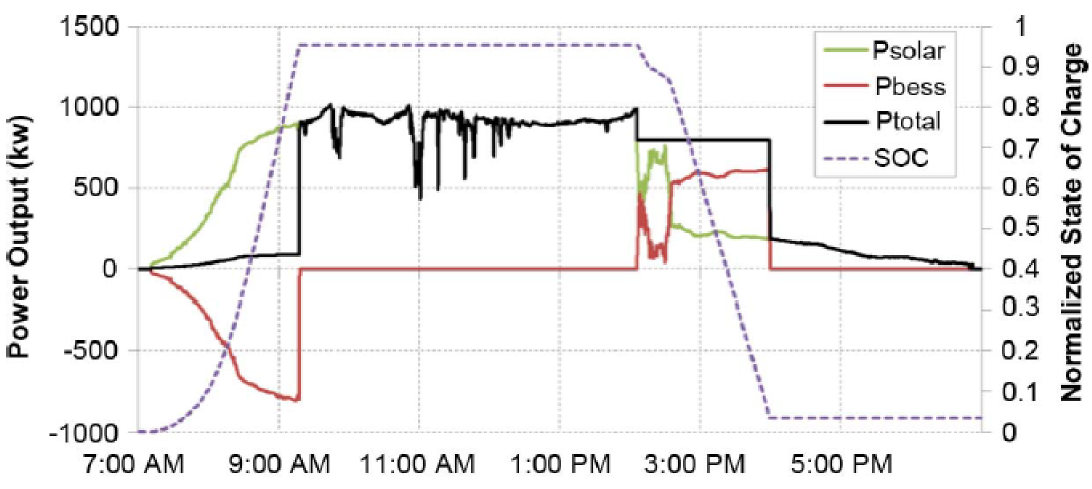

Figure 24: Solar Time Shift full day output

Reactive Power Support

An important technical challenge for electric grid system operators is to maintain necessary voltage levels with the required stability. A distribution feeder will typically employ a combination of voltage regulators and switched or static shunt capacitors to deliver power at a consistent voltage and power factor to all customers on the line. Power factor pf is defined as

$$pf = \frac{P}{S} = \cos\theta \qquad (5)$$

where P is the real power flow (in Watts), S is the apparent power flow (in Volt-Amperes or VA), and θ is the angle difference between the voltage and current waveforms on a given phase. Power factor is continuously variable between 0 and 1, and can be either leading or lagging. Lagging power factor indicates a component that absorbs reactive power (in Vars), while a leading power factor component is said to generate reactive power. The natural inductance of overhead power lines, transformers, and many kinds of loads results in the absorption of reactive power and a low, lagging power factor. The lower the power factor, the more current must flow on the line to supply a given power P as governed by the basic AC power equations [48]. Therefore, it is desirable to maintain a pf near 1.0 in order to minimize insulation requirements as well as losses due to I^2R and I^2X losses, and to counteract voltage drop across the system impedance.

On AC power distribution systems, voltage is a local phenomenon strongly affected by reactive power flows. Switched capacitors are often installed on the bus to provide reactive power and regulate voltage. The capacitors may be switched in and out of the circuit several times a day because reactive power needs fluctuate according to load. The change in voltage from the insertion of a capacitor is approximated as

$$\text{Percent } \Delta V = \frac{kvar_{cap} \times Z_{tx}}{kVA_{tx}} \quad (6)$$

where ΔV is the change in voltage, $kvar_{cap}$ is the rating of the capacitor, Z_{tx} is the per-unit impedance of the upstream step-down transformer, and kVA_{tx} is the step-down transformer rating. This formula uses the step-down transformer rating as an approximation of the local stiffness of the grid, which is acceptable as the transformer typically provides the majority contribution to the system total impedance at the point of capacitor installation [64]. Shunt capacitor banks are cheap and effective at providing reactive power support, but have drawbacks in terms of large switching transients, and the "all-or-nothing" nature of switching the bank in. Reactive support with power electronics enables continuous changing of the reactive power delivered into the system with no transients, and this capability comes with no extra equipment necessary once a BESS has been installed.

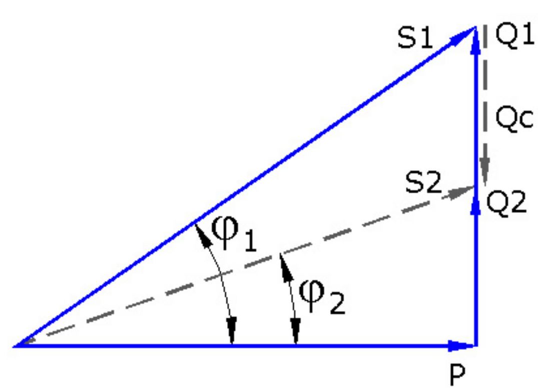

Figure 25: The power triangle, relating P, Q, S, φ, and power factor.

The four-quadrant power electronic converter on a BESS can inject reactive power to the bus to maintain either a power factor or voltage setpoint on the bus, providing improved system efficiency, and lower losses. When maintaining a given power factor, the power triangle can be used as depicted in Fig. 26. Applying trigonometry to the power triangle and substituting in equation 5, we see that the necessary reactive power correction QC to move from an initial power factor of Q1 to Q2 is equal to

$$Q_C = P[tan(cos^{-1} \varphi_1) - tan(cos^{-1} \varphi_2)] \tag{7}$$

and Q can be readily adjusted to maintain the desired power factor as the measured real power P at the bus changes.

The benefits of improved power factor can be quantified as reduced power system losses % $\text{loss}_{\text{reduction}}$, and reduction in line current $\%\Delta I$ upline of the reactive power source, whether capacitor or BESS. These benefits are quantified according to:

$$\%\ \text{loss}_{\text{reduction}} = 100\left[1 - \left(\frac{pf_{original}}{pf_{corrected}}\right)^2\right] \tag{8}$$

$$\%\Delta I = 100\left[1 - \left(\frac{\cos\theta_{original}}{\cos\theta_{corrected}}\right)\right] \tag{9}$$

where pf is power factor, and $\cos\theta$ is the power factor angle from the power triangle [64].

IV. CONCLUSION

This report has presented an overview of the technology and literature pertaining to the design of grid-scale battery energy storage systems for various applications, including battery technology, power electronics, and control systems. Energy storage systems can be used for a wide range of applications, and each application presents a unique set of design constraints to work within. Issues such as power rating, event duration, and the application duty cycle must be well understood in order to select the best combination of technologies to accomplish the performance requirements of the system in a safe and cost-effective manner.

With the technology available today, it is generally the case that lead acid and lithium ion based batteries are the best choice for most applications with durations less than two hours, while molten sodium batteries begin to become competitive in systems requiring several hours of capacity. Lead acid batteries are very safe and low cost, but their lower cycle life and sulfation issues at low states of charge may rule them out for certain applications such as ramp rate control. Lithium ion technology represents a range of different competing chemistries including LMO, NCA, LFP, and LTO in the grid-scale energy storage space. Batteries with Lithium Titanate or LTO negative electrode materials are the safest, longest lasting, and have the highest charge and discharge power ratings, but are also the most expensive, limiting their use to applications with aggressive duty cycles and short durations in most cases, such as frequency regulation and response. The other lithium ion chemistries all use graphite for their negative electrode, and offer better energy density and lower cost at the expense of safety and cycle life. Since safety is of paramount importance with very large storage systems, NCA is viewed by the author as a relatively poor choice for grid-scale storage, requiring very conservative operation by the control system to prevent thermal runaway. LMO and LFP are inherently safer chemistries, and may be good choices for applications such as renewable energy integration and providing fast-responding reserve capacity to the power system operator. Sodium sulfur and sodium nickel chloride chemistries are not capable of high-power operation in the form that is available today. These sodium-based batteries are a good choice for long-duration low power applications, and their ability to operate over the widest range of ambient conditions is a valuable asset, given the remote locations where energy storage is often most valuable.

All battery energy storage systems require power electronic interfaces to convert the DC power of the batteries to AC power used on the electricity grid. These conversion devices must be designed to meet both the battery and grid requirements, which include voltage, current, and response time specifications, as well as meet the requirements of several technical standards for power quality, harmonic content, and voltage and frequency ride-through settings. The operation of the power conversion system must be carefully controlled to safely meet the needs of the grid operator and to maximize the life of the batteries. The control systems for battery energy storage systems include a battery management system and a power conversion system controller at a minimum, and usually feature a master controller that interfaces between these lower level control devices and the system operator as well as various metering and telemetry devices.

The grid-scale energy storage market has been growing exponentially over the last several years. As new technologies continue to move from the laboratory to the field, it should be expected that many of the considerations described above will become outdated with time. It is hoped that this paper has given the reader a useful overview of the present state of the technology, and that the information may also help in understanding, evaluating, and engineering the new technologies and new applications that emerge in this field going forward.

REFERENCES

[1] Nourai, A., & Schafer, C. (2009). Changing the electricity game. Power and Energy Magazine, IEEE, 7(4), 42-47.

[2] N. Miller, D. Manz, J. Roedel, P. Marken, and E. Kronbeck, "Utility scale battery energy storage systems" in Proc. IEEE Power Energy Soc. Gen. Meeting, Minneapolis, MN, Jul. 2010.

[3] Nourai, R. Sastry, and T. Walker, "A vision & strategy for deployment of energy storage in electric utilities," in Proc. IEEE Power Energy Soc. Gen. Meeting. Minneapolis, MN, Jul. 2010.

[4] D. Linden and T. B. Reddy, (2011). Chapter 1. *Linden's Handbook of Batteries* (Vol. 4). McGraw-Hill

[5] Joerissen, L., Garche, J., Fabjan, C., & Tomazic, G. (2004). Possible use of vanadium redox-flow batteries for energy storage in small grids and stand-alone photovoltaic systems. *Journal of power Sources*, *127*(1), 98-104.

[6] OHMORI, S., & YAMAMOTO, T. (2010). *WIPO Patent No. 2010110465*. Geneva, Switzerland: World Intellectual Property Organization.

[7] Bradwell, D. J., Kim, H., Sirk, A. H., & Sadoway, D. R. (2012). Magnesium–Antimony Liquid Metal Battery for Stationary Energy Storage. *Journal of the American Chemical Society*, *134*(4), 1895-1897.

[8] Battery University, Types of Lithium Ion. Available Online: http://batteryuniversity.com/learn/article/types_of_lithium_ion

[9] NGK Insulators: NAS Battery Fire Incident and Response. Available Online: http://www.ngk.co.jp/english/announce/

[10] Boeing Reveals 787 Battery Fix Details. Available Online: http://www.aviationweek.com/Article.aspx?id=/article-xml/AW_03_18_2013_p28-559071.xml&p=1

[11] Valve-Regulated Lead Acid Batteries, D.A.J. Rand, P.T. Mosely, J. Garche, and C.D. Parker, Ed's. Amsterdam, The Netherlands: Elsevier, 2004, pp. 295-326.

[12] A. Akhil, J. Boyes, P. Butler, D. Doughty (2011). Chapter 30. *Linden's Handbook of Batteries* (Vol. 4). McGraw-Hill

[13] N. W. Miller, R. S. Zrebiec, R. W. Delmerico, and G. Hunt, "Design and commissioning of a 5 MVA, 2.5MWh battery energy storage," in Proc. 1996 IEEE Power Engineering Society Transmission and Distribution Conf., 1996, pp. 339-345

[14] "Analysis of a Valve-Regulated Lead-Acid Battery Operating in Utility Energy Storage System for more than a Decade" – George Hunt, GNB Industrial Power – A Division of Exide Technologies, Energy Storage Association May 2009

[15] Huggins, Robert A. *Energy storage*. Springer Verlag, 2010

[16] R. H. Newnham, W.G.A. Baldsing, "Advanced management strategies for remote-area power supply systems," in Journal of Power Sources 133 (2004), pp. 141-146

[17] C&D Technology, Parallel Operation of Lead Acid Batteries. Available online: http://www.cdtechno.com/pdf/ref/41_7952_0112.pdf

[18] Batteries Common Wastes and Materials | EPA. Available Online: http://www.epa.gov/osw/conserve/materials/battery.htm

[19] K. Mizushima, P.C. Jones, P.J. Wiseman, J.B. Goodenough. "Li_xCoO_2 (0<x<-1): A new cathode material for batteries of high energy density" in Materials Research Bulletin Volume 15, Issue 6, 1980, pp. 783-789

[20] T. Nagaura and K. Tozawa, Prog. Batt. Solar Cells, 9, 209, (1990)
[21] J. McDowall. "Understanding lithium-ion technology." Battcon, Marco Island, FL (2008).
[22] J. McDowall, P. Biensan, M. Broussely. "Industrial lithium ion battery safety – What are the tradeoffs?." Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International. IEEE, 2007.
[23] Samsung SDI White Paper: Available Online: http://www.samsungsdi.com/storage/energy-storage-products.jsp#p_3_4_5t_dfn1
[24] J.B. Goodenough, A.K. Padhi, K.S. Nanjundaswamy, and C. Masquelier, "Cathode materials for secondary (rechargeable) lithium batteries," US Patent 5,910,382, June 8, 1999
[25] Shenouda, A. Y., & Murali, K. R. (2008). Electrochemical properties of doped lithium titanate compounds and their performance in lithium rechargeable batteries. *Journal of Power Sources*, *176*(1), 332-339.
[26] Toshiba SCiB Product Page. Available Online: http://www.scib.jp/en/
[27] Bito, A. (2005, June). Overview of the sodium-sulfur battery for the IEEE Stationary Battery Committee. In *Power Engineering Society General Meeting, 2005. IEEE* (pp. 1232-1235). IEEE.
[28] A. Akhil, J. Boyes, P. Butler, D. Doughty (2011). Chapter 30. *Linden's Handbook of Batteries* (Vol. 4). McGraw-Hill
[29] Mohan, N., Undeland, T. M., & Robbins, W. P. (1997). Power electronics: converters, applications and design, 1995.
[30] M. Sippola, W.L. Klampfer, "LCL Filter Design for PWM Rectifiers," Available Online: http://www.yorkemc.co.uk/conferences/emcYork2004/synopsis/Wolfgang%20Klampfer%20-%20LCL%20filter%20design.pdf
[31] "Nema Enclosure Types" Available Online: http://www.nema.org/Products/Documents/nema-enclosure-types.pdf
[32] Basso, T. S., & DeBlasio, R. (2004). IEEE 1547 series of standards: interconnection issues. *Power Electronics, IEEE Transactions on*, *19*(5), 1159-1162.
[33] UL 1741 | Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources. Available Online: http://ulstandardsinfonet.ul.com/tocs/tocs.asp?fn=1741.toc
[34] Duffey, C. K., & Stratford, R. P. (1989). Update of harmonic standard IEEE-519: IEEE recommended practices and requirements for harmonic control in electric power systems. *Industry Applications, IEEE Transactions on*, *25*(6), 1025-1034.
[35] A. Jossen, "Battery Management," in Valve-Regulated Lead Acid Batteries, D.A.J. Rand, P.T. Mosely, J. Garche, and C.D. Parker, Ed's. Amsterdam, The Netherlands: Elsevier, 2004, pp. 295-326
[36] D. Andrea, Battery Management Systems for Large Li-Ion Battery Packs, Norwood: Artech House, 2010
[37] G. Plett. (2004) "Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs: Parts 1-3," Journal of Power Sources, Vol 134 Issue 2
[38] Piller, S., Perrin, M., & Jossen, A. (2001). Methods for state-of-charge determination and their applications. Journal of power sources, 96(1), 113-120.
[39] Bergveld et al 2002 Battery Management Systems, Design by Modelling (Phillips Research Book Series) vol 1 (Boston: Kluwer)
[40] Cao, J., Schofield, N., & Emadi, A. (2008, September). Battery balancing methods: A comprehensive review. In Vehicle Power and Propulsion Conference, 2008. VPPC'08. IEEE (pp. 1-6). IEEE.

[41] Kimball, J. W., Kuhn, B. T., & Krein, P. T. (2007, September). Increased performance of battery packs by active equalization. In Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE (pp. 323-327). IEEE.

[42] St. John, J. "Xtreme Power to Sell Battery Factory, Focus on Software." Greentech Media. Available Online: http://www.greentechmedia.com/articles/read/xtreme-power-to-sell-battery-factory-focus-on-software

[43] Kelly-Detwiler, P. "One Company's Approach to Innovation in Electricity Storage: Focus on the Software." Forbes. Available Online: http://www.forbes.com/sites/peterdetwiler/2013/02/26/one-companys-approach-to-innovation-in-electricity-storage-focus-on-the-software/

[44] PUD. "Snohomish PUD & 1Energy Partner on Energy Storage Innovation." Lake Stevens Journal. Available Online: http://www.lakestevensjournal.com/county-state/article.exm/2012-12-05_snohomish_pud___1energy_partner_on_energy_storage_innovation

[45] J. Eyer and G. Corey, (2010, Feb.) "Energy Storage for the Electricity Grid" Sandia Nat'l Labs Publications. Available Online: http://www.sandia.gov/ess/publications/pubslist_05.html

[46] EPRI Report: Electricity Energy Storage Technology Options, Available online: www.epri.org

[47] Sempra Auwahi Wind & Energy Storage – Presentation to UH Maui. Available Online: http://www.hawaiicleanenergyinitiative.org/storage/media/8_Sempra%20Auwahi%20Wind%20and%20Energy%20Storage.pdf

[48] J. D. Glover, M.S. Sarma, T.J. Overbye, Power System Analysis and Design, Stamford: Cengage, 2008, p. 698.

[49] F. Katiraei and J. R. Aguero. (2011, May/June) Solar PV Integration Challenges. IEEE Power & Energy Magazine. Available Online: http://www.ieee.org/organizations/pes/public/2011/may/index.html

[50] B. Kroposki, et al, (2012, Jun.) "Integrating High Levels of Renewables into the Lanai Electric Grid" National Renewable Energy Laboratory Technical Report. Available Online: http://www.nrel.gov/docs/fy12osti/50994.pdf

[51] A. Akhil, A. Murray, and M. Yamane, (2009, Jun.) "Kauai Island Utility Cooperative Energy Storage Study" Sandia Nat'l Labs Publications. Available Online: http://prod.sandia.gov/techlib/access-control.cgi/2009/092679.pdf

[52] P. Kundur, Power System Stability and Control, New York: McGraw-Hill, 1994, pp. 589-594

[53] J.F. Ellison, L.S. Tesfatsion, V.W. Loose, R.H. Byrne, (2012, Sep) "Project Report: A Survey of Operating Reserve Markets in U.S. ISO/RTO-managed Electric Energy Regions" Sandia Nat'l Labs Publications. Available Online: http://www.sandia.gov/ess/publications/SAND2012_1000.pdf

[54] FERC Order 755. Available Online: https://www.ferc.gov/whats-new/comm-meet/2011/102011/E-28.pdf

[55] PJM News Release: "PJM implements innovative pay for performance model for regulation service" Available Online: http://www.pjm.com/~/media/about-pjm/newsroom/2012-releases/20121002-performance_based_regulation_implemented.ashx

[56] Business Wire, Daily Finance. "AES Marks Energy Storage Milestone with 400,000 MWh of PJM Service from Laurel Mountain" Available Online: http://www.dailyfinance.com/2013/04/11/aes-marks-energy-storage-milestone-with-400000-mw-/

[57] Duke Energy News Release: "Duke Energy Renewables completes Notrees Battery Storage Project in Texas; North America's largest battery storage project at a wind farm." (2013, Jan) Available Online: http://www.duke-energy.com/news/releases/2013012301.asp

[58] F. Katiraei and J. R. Aguero. (2011, May/June) Solar PV Integration Challenges. IEEE Power & Energy Magazine. Available Online: http://www.ieee.org/organizations/pes/public/2011/may/index.html

[59] U.S. Patent No. 20110273129, "Managing Renewable Power Generation", 2011, Xtreme Power

[60] Such, M. C., & Hill, C. (2012, January). Battery energy storage and wind energy integrated into the Smart Grid. In Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES (pp. 1-4). IEEE.

[61] M. Black, G. Strbac, "Value of storage in providing balancing services for electricity generation systems with high wind penetration," Journal of Power Sources, vol. 162, no 2, pp. 949-953, Nov. 2006.

[62] Hill, C. A., Such, M. C., Chen, D., Gonzalez, J., & Grady, W. M. (2012). Battery energy storage for enabling integration of distributed solar power generation.Smart Grid, IEEE Transactions on, 3(2), 850-857.

[63] R.H. Byrne, C.A. Silva-Monroy (2012, Dec) "Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation" Sandia Nat'l Labs Publications Available Online: http://www.sandia.gov/ess/publications/SAND2012-3863.pdf

[64] R. C. Dugan, M. F. McGranaghan, S. Santoso, H. W. Beaty, *Electrical Power Systems Quality*, New York: McGraw-Hill, 2002, p. 295